Quality of potatoes from a sustainability perspective

by

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by
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ABSTRACT

Nutrient-sensitive, sustainable agricultural production to ensure food and nutrition security is currently a topic of great global interest. The need to provide planet-friendly foods that are affordable, nutrient-rich, socially appealing and culturally acceptable, presents a challenge that agricultural food systems must address. The Sustainable Development Goals of the United Nations demand healthy and diverse food systems. Staple foods, such as bread, potatoes (the only non-grain staple food), rice and maize meal, play an important role in food security in Sub-Saharan Africa. The annual per capita consumption of staple foods in South Africa is dominated by maize meal (50.4kg), followed by potatoes (39.3kg), bread (25.8kg) and rice (18.6kg). Research on sustainability in relation to the nutrient contribution these staple food commodities provide to the diets of South Africans is lacking. In this study the nutrient density of the most commonly consumed staple foods was analysed and its environmental impact was measured. Potatoes had the lowest greenhouse gas emission value per unit of nutrient density and energy, and the lowest water footprint compared to maize meal, bread, pasta and rice.

Due to the increased interest in the metabolic effect of specific individual dietary amino acids, especially from alternative, non-animal sources, the protein and amino acid contents of four different potato cultivars were determined. It was found that potatoes contain small quantities of high quality protein that can contribute to the overall protein content of the diet.

In the next part of the study, a robust postharvest method was developed to describe the intrinsic quality of potatoes as influenced by external conditions. It was hypothesised that specific attributes can be used to group potatoes together that display similar internal properties. A guide was developed to improve the utilisation potential of fresh potatoes. As a first step to explore this hypothesis, the cultivars with the largest market share were identified. These cultivars were then sampled from ten different experimental plots across South Africa over a period of three years to determine the effect of external factors on internal quality. The agricultural practices used in these areas, were those normally applied by farmers in such areas. It was found that, irrespective of region, external conditions such as rain, temperature, fertilizer and soil type had a greater effect on the internal attributes of potatoes than cultivar specific differences. Due to the finding that cultivar is not a reliable predictor of internal attributes, more reliable measures for classification were sought and investigated.

Dry matter content was found to be the most robust and reliable parameter to use, followed by specific gravity. The determination of specific gravity is a method that is commonly employed by industry and scientists to determine the processing suitability of fresh potatoes. However, to be able to determine either dry matter content and/or specific gravity, a certain level of precision and some equipment are required. This implies that neither measurement can be readily carried out at farm level. Thus the need for farmers to be able to describe their harvested potatoes at farm level remained a challenge. Consequently, the study was expanded to develop an easily repeatable and reliable, scientifically validated method to classify potatoes post-harvest. Different cooking methods and cutting procedures were tested to develop a suitable methodology. A standardised boiling test proved to deliver consistent and reliable results when classifying potatoes per batch. A visual guide to the appearance of the potato wedges with an easy understandable description was developed. Tubers subjected to the specific boiling test exhibit specific cultivar-intrinsic visual characteristics which can then be compared to the predetermined standardised visual guide.

In conclusion, the study revealed that potatoes have the lowest environmental impact, when compared to other staple foods such as maize meal, bread, pasta and rice. Potatoes contain small quantities of high quality protein, which can boost the protein quality of the diet. Dry matter is the most reliable and robust method for determining internal textural characteristics. Cultivar type was not a reliable indicator of potato intrinsic attributes. A standardised cooking test, together with a visual guide, was developed, to classify potatoes at farm level. This test should prove useful to the global potato industry.

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List of acronyms

AA	Amino Acid
AMMI	Additive Main-effects and Multiplicative Interactions
ANOVA	Analysis of Variance
AOAC	Association of Official Agricultural Chemists
ARC	Agricultural Research Council
BCAA	Branched Chain Amino Acids
BRICS	Brazil, Russia, India, China and South Africa
CERES	Ceres
CI	Confidence Interval
CO2	Carbon Dioxide
CS	Chemical Score
CSEAA/CS	Chemical Score of the Essential Amino Acids
C-W	Cold to Warm
DAFF	Department of Agriculture Forestry and Fishery
DIAAS	Digestible Indispensable Amino Acid Score
DM	Dry Matter
DST	Department of Science and Technology
dti	Department of Trade and Industry
DV	Daily Value
EAAI	Essential Amino Acids Index
EC	Eastern Cape
ED	Energy Density
EFS	Eastern Free State
Env	Environment
Eq	Equation
FAO	Food and Agricultural Organisation
FBDG	Food Based Dietary Guidelines
FDA	Food and Drug Administration
FPLSD	Fisher's Protected Least Significant Difference
FSA	Food Standards Agency
GDP	Gross Domestic Product
Gen	Genome
GHGE	Greenhouse Gas Emission
GI	Glycaemic Index
GT	Gauteng
ha	Hectare
HPLC	High-Performance Liquid Chromatography
HV	Mpumalanga Highveld
ILSI	International Life Science Institute
IPC	Interaction Principal Component
IUCN	International Union for Conservation of Nature
K	Potassium
kcal	Kilo Calorie
kJ	KiloJoule
KZN	Kwa-Zulu Natal
LCA	Life Cycle Assessment
LIM	Limited Nutrient Score
LIM	Limpopo
MDG	Millennial Development Goals

MH	Mpumalanga
MRV	Maximum Recommend Value
N	Nitrogen
NC	Northern Cape
ND	Nutrient Density
NDCI	Nutrient Density Score to Climate Impact
NEC	North Eastern Cape
NIDDM	Non-Insulin Dependent Diabetes Mellitus
NR	Nutrient Rich
NR	Nutrient Reference
NRF	Nutrient Rich food
NRF	National Research Foundation
NW	North West
P	Phosphorus
PCA	Principal Components Analysis
PDCAAS	Protein Digestibility Corrected Amino Acid Score
PLS	Partial Least Square Regression
PSA	Potatoes South Africa
RACC	Reference Amounts Customarily Consumed
RBD	Randomized Block Design
RDA	Recommended Dietary Allowance
REML	Restricted Maximum Likelihood
SAIN	Score of Nutritional Adequacy of Individual Foods
SANAS	South African National Accreditation System
SAND	Sandveld
SC	Southern Cape
SDG's	Sustainable Development Goals
SG	Specific Gravity
SUGIRS	Sydney University Glycemic Index Research Service
SVD	Singular Value Decomposition
SWFS	South Western Free State
UN	United Nations
USDA	United Sates Department of Agriculture
W-C	Warm to Cold
WFS	Western Free State
WHO	World Health Organisation

Chapter 1: The study in perspective - Sustainability of potatoes from a nutrition perspective

"In the end, we are still left with the confusing question: Are we born this way, or do we behave according to our life experiences? The nature vs nurture debate goes on and on, but still, it is a fact that we have traits that are predetermined by our genes, but we can still choose who we want to be as we travel through our lifetime." – Lewis, T (2012)

1.1 Introduction

It is estimated that there are over 50 000 edible plant species on earth, yet rice, maize and wheat make up 60% of global energy intake. Rice, wheat, maize (corn), millet, sorghum, roots and tubers (potatoes (*Solanum tuberosum L.*), cassava, yams and taro), are regarded as the main global staple crops. Of the 50 000 edible plant species on earth only 15 of these crops provide 90% of the world's daily energy intake earning them the title of staple foods (Food and Agricultural Organisation, 2011). These three staples, rice, maize and wheat, together with potatoes, are the four most commonly consumed global crops (Zaheer & Akhtar, 2016) (Figure 1-1). The role of roots and tubers is especially important in the developing world, playing an essential part in the diet of over a billion people as a main source of staple food. The FAO defines a staple food as "*one that is eaten regularly and in such quantities as to constitute the dominant part of the diet and supply a major proportion of energy and nutrient needs".* In Africa, the average dietary energy intake is made up of 46% cereals, 20% roots and tubers and 7% animal products. The remainder consists of various foods from different food groups that are region specific. This emphasizes the remarkable role of staple foods, particularly maize, in the diet, as it accounts for about 40% of the total food consumed by half the population of sub-Saharan Africa. European countries have a higher intake of animal products (33%), followed by cereals (26%) and roots and tubers (4%). The rest of the equation is made up of fruits, vegetables, and processed foods (Food and Agricultural Organisation, 2011).

The staple foods of a region normally attain this position thanks to their affordability, their adaptations to the area in which they grow fairly easily and the fact that they are well adapted to the agricultural demographics of that area. These foods are also familiar to the local population, not only with regard to preparation and cooking, but are also culturally acceptable. In agricultural and economical terms staple foods are often considered as low risk crops for farmers due to the somewhat consistent demand for these foods, which also contributes to the resilience of the agricultural system. Reliable research on staple foods is a powerful tool that can lead to the enhancement of knowledge relating to these crops. Intervention actions, such as bio-fortification, precision farming and agricultural education can ensure that the value of these foods to vulnerable individuals is fully promoted by the nutrition and public health community (Nestel, et al., 2006).

Potatoes have a unique place within the staple food domain and are classified as a global crop that contributes to health and well-being. Potatoes originated in South America from where they spread to Europe, Asia and Africa. Over the past five centuries, they have been adapted to be cultivated as indigenous crops because they are able to acclimatise to a wide array of agricultural and climatic variables. It is estimated that tubers are commercially cultivated in more than 160 countries in the world. Potatoes are, therefore, considered an international food commodity. Potatoes had an estimated global production value of 368 million tonnes in 2015 and a global mean per capita consumption rate estimated at 33kg/year (King & Slavin, 2013; FAO, 2019). Over the past 30 years a dramatic increase was observed in the consumption of potatoes in developing countries. Production values rose by over 30% compared to the early 1980s when less than 20% of tubers were produced and consumed. In developing countries potatoes are mostly consumed in the form of deep fried chips or crisps (FAO, 2008).

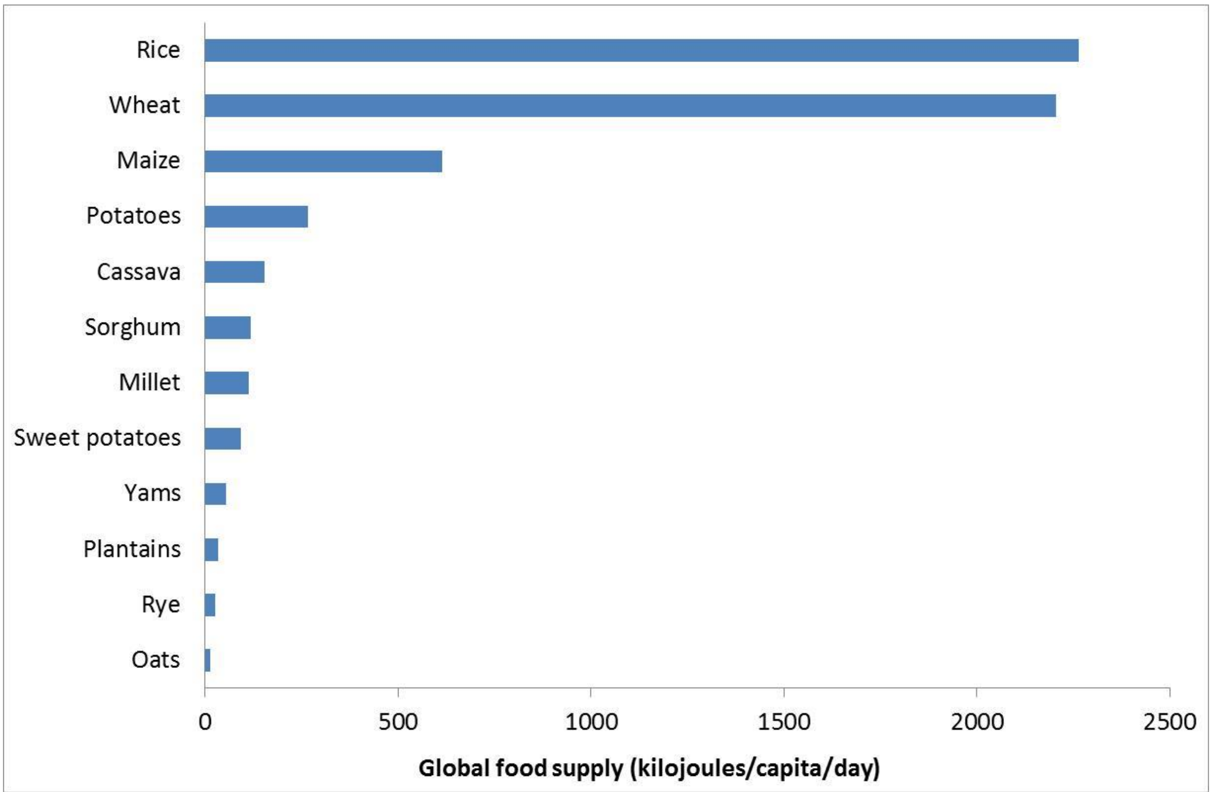

Figure 1-1: The most commonly consumed starch-rich staple foods at a global level in 2013 (FAO, 2017)

The increasing pressure of a growing population is evident in changing food systems, which inevitably also change the agricultural sector. Increased agricultural outputs are required despite the need for a reduction in resource usage (e.g. land and water). In an attempt to ensure that an equilibrium is reached, an increasing number of research goals and programmes are focused on ensuring resource use efficiency in this sector. In this regard numerous publications from various countries continue to report on the contribution of agriculture to greenhouse gas emissions; a contribution which is estimated to equal 24%. Thus production and consumption of food find themselves under the spotlight in relation to sustainable production (Clark & Tilman, 2017; Gernett, 2011; Friel, et al., 2009). Promoting and supporting nutrient sensitive diets involves balancing the relationship between nutrients provided by food and the effect the specific food has on the environment. Discussions on the implementation of policies and programmes that attempt to achieve these nutrient sensitive diets occur at international levels as is evident in the Sustainable Development Goals and the Decade of Action on Nutrition (United Nations, 2018).

Furthermore, the recently launched EAT-Lancet Healthy Diets from Sustainable Food Systems argues the point that food and, by direct contribution, the agricultural system, has the single strongest potential to alleviate a wide array of human diseases and contribute to sustainable development. Even though globally the agricultural sector is able to produce sufficient food for all, there are more than 820 million people who lack sufficient amounts or quality of food (food insecure). The high prevalence and increase in unhealthy diets is becoming one of the paramount threats to mankind. Not only does the food we eat have a major influence on our health, but the way in which it is produced threatens stability and ecosystem resilience. This combined burden that food choices place on the health system, as well as the environment, may prove to be one of the greatest challenges of our time. This challenge also provides an interesting and vast field of study which offers opportunities for country and commodity specific research to contribute to global scientific targets (EAT-Lancet , 2019).

Together with the call to action by international stakeholders, pressure from downstream role players is a constant for the agricultural sector. Consumer choice remains one of the largest drivers of production outcomes, as there is no sense in producing a product that is not wanted or more specifically accepted by the consumer market. The way in which food products are classified, as well as their adherence to classification systems, has a remarkable impact on consumer acceptability and utilisation of the product. Previous experiences form the basis of consumer expectations and a set of sensory information is formed from experiences of the internal and external inherent physico-chemical characteristics of a product (Cardello, 1994). Therefore, consistency of a food product is of immeasurable value when it comes to consumer acceptance and utilisation of the product. However, achieving consistency with a single agricultural product is not easy to accomplish. Aiming to achieve a standardised classification system by means of a synthesised programme that is based on robust scientific evidence can be valuable to the potato industry to ensure that consistency is achieved and consumer desires and prerequisites are met. This can also be adapted in the processing sector where fine margins are required for profitability. However, the latter topic will not be discussed in this thesis.

The ever changing consumer market and the constantly developing concept of innovation within a sustainable world have led to a dire need to balance consumer expectations, while adhering to environmental outcomes, as well as nutritional needs. This provides the agricultural sector with a unique opportunity to align production practices with suitability goals to gain traction within a consumer market to promote nutritionally high quality diets that support sustainable food systems.

1.2 Background to the study

1.2.1 Defining quality

One of the best known and most quoted definitions that is still used 30 years later is that of Hofmann: "Quality can be best defined as that which the public likes best and for which they are prepared to pay more than average prices" (Hofmann, 1990). With this perception of today's consumers' preference for quality has been defined as comprising four aspects of importance along with a new fifth addition of sustainability:

- Visual quality: all external aspects including shape, size, skin finish and wash
- Eating quality: Internal texture, aroma, flavour and mouthfeel
- Nutritional quality: Proportions of proteins, vitamins, and minerals relative to energy density
- Safety: Negligible risk from food-borne illness or poisoning and absence of drugs and chemicals
- Sustainability.

1.2.2 Defining sustainability

Sustainability has become an international buzzword with far reaching effects and consequences. The need for research and policy development on this topic, as discussed at global stakeholder meetings such as the International Union for Conservation of Nature (IUCN) in October 1948 in Fontainebleau, France has since then become an imperative part of global development. In 1972, the Club Rome hosted a think-tank which consisted of a small group of international stakeholders from various fields of expertise, who came to the realisation that something will have to give, should economic growth continue at the then unprecedented rate considering the limited availability of natural resources. In the same year at the United Nations Conference on the Human Environment in Stockholm, a concept was developed that postulated that "*it was possible to achieve economic growth and industrialization without environmental damage".*

In the years that followed, after these thought processes were the concept of sustainability and its effect on the human population was further developed through the World Conservation Strategy in 1980, the Brundtland report of 1987, which provided one of the first definitions for sustainability, and the United Nations Conference on Environment and Development in Rio (1992). Apart from high level discussions held at international levels, national governments, business leaders and non-governmental organisations started mainstreaming the idea of sustainable production. In 2002 the World Summit on Sustainable Development, hosted in Johannesburg, contributed towards elevating sustainable development up on the political agenda.

Many issues and unforeseen hurdles in the form of multiple global challenges encompassing various sectors have been experienced since the 2002 summit. Consequently, in 2009 the United Nations General Assembly decided to host the United Nations Conference on Sustainable Development in Rio in 2012 to address these issues, as well as to plan the way forward. This conference resulted in a streamlined political outcome document which contained clear and practical measures to address issues pertaining to sustainable development. This was complemented by the launch of the Sustainable Development Goals (SDGs), which were based on the Millennium Development Goals (MDGs). The SDGs are the current focus of sustainability actions (United Nations, 2018). The relevance of these goals to nutrition will be discussed later.

Continuous actions are taking place, the United Nations Climate Action Summit, which was held in September 2019 in New York, is but one example. The aims of this summit anticipate to *"confront the worsening climate crisis by delivering new pathways and practical actions to shift global response into higher gear".* One of the main take-home-messages from the summit was the need for united action to achieve the goals as set out in the Paris Agreement. At this summit, António Guterres, the United Nations Secretary-General said: "*This is not a climate talk summit. We have had enough talk, this is not a climate negotiation summit. You don't negotiate with nature. This is a climate action summit".* He encouraged countries to take individual actions and become part of the bigger picture by deploying resources in fundamentally new and meaningful ways to ensure sustainable outcomes (UN, 2019).

Since its conception in 1988, the definition of sustainable development "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* as introduced in the Brundtland Report for the World Commission on Environment and Development has evolved considerably (Keeble, 1988). Even though there are various definitions for sustainability, the goal remains clear – "*avoidance of the depletion of natural resources in order to maintain an ecological balance."* The paradox of sustainability lies with two fundamental issues: the need for economic growth which has accompanying detrimental effects on the environment coupled with the need for such growth, to alleviate poverty and improve quality of life. Therefore, when considering sustainability approaches the three interdependent pillars (Figure 1-2) on which sustainability stands, namely; economic development, social development, and environmental protection, need to be evaluated to ensure effective integration and contributions to decision making (Figure 1-3) (OECD, 2018; McCormick, 1991).

The impact of food production on the environment and the necessity for sustainable nutrient sensitive diets are increasingly included in the conversation regarding sustainable development on a global level and woven into the SDGs. Goals that are relevant to sustainable food production include: Goals 2, 12 and 13 of the SDGs, that are also very specifically related to the project which forms the basis of this thesis.

Goal 2: End hunger and improve nutrition, and promote sustainable agriculture.

Goal 12: Ensure sustainable consumption and production patterns.

Goal 13: Take urgent action to combat climate change and its impacts.

Promoting and supporting nutrient sensitive diets involves balancing the relationship between nutrients provided by food compared to the effect the specific food has on the environment. Discussions on the implementation of policies and programmes to achieve these nutrient sensitive diets occur at international level as is evident in the SDGs.

The three goals (2, 12 &13) encompass the concept of sustainable food production to ensure food for future generations. To achieve these goals forward thinking is required in the way food is grown, shared and consumed. The food and agriculture sector offers key solutions for development, and is central for hunger and poverty eradication. By encouraging sustainable production methods and buy in from industry, the implementation of these plans can help to achieve overall development plans, reduce future economic, environmental and social costs, strengthen economic competitiveness and reduce poverty.

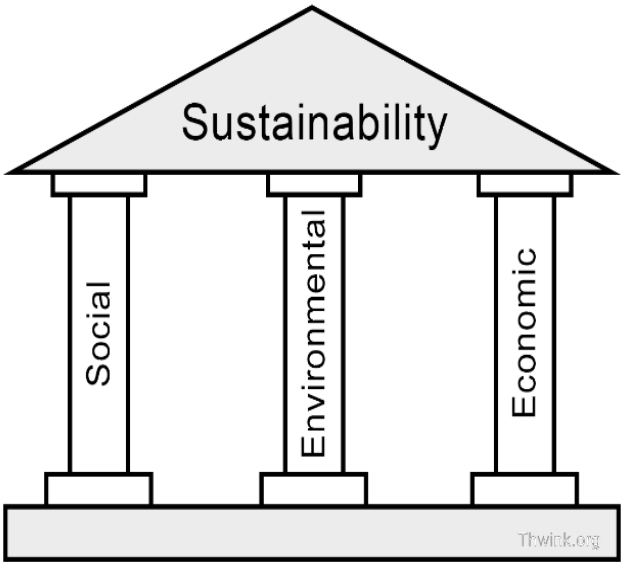

Figure 1-2: Three pillars of sustainability (UN, 2019)

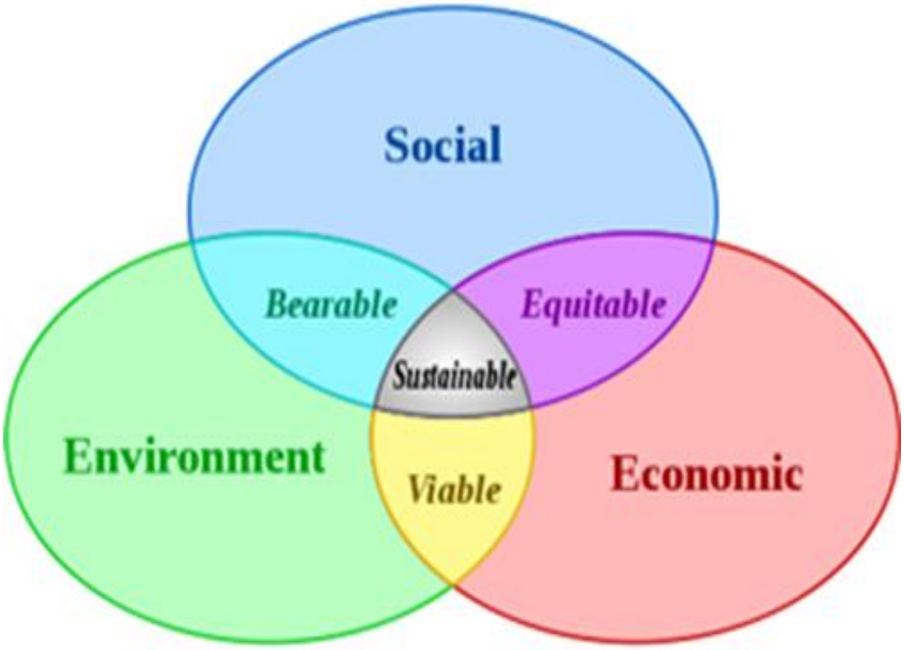

Figure 1-3: Three pillars of sustainability depicted as interlinking circles (UN, 2019)

Climate change remains a global challenge in that it does not respect national borders, race, ethnicity or beliefs. Emissions anywhere affect people everywhere. Therefore, issues of climate change require solutions that are coordinated at an international level. Through research and development, affordable, scalable solutions have become available that enable countries to leapfrog to cleaner, more resilient economies that will contribute to the goal of feeding an extra 2 billion people by 2050 (Figure 1-4) (UN, 2018).

Sustainable consumption and production is about promoting resource and energy efficiency, sustainable infrastructure, and a better quality of life for all. If conducted in a sustainable manner, agriculture, forestry and fisheries can deliver nutritious food for all and generate liveable incomes, while supporting people-centred rural development and protecting the environment. It also requires a systemic approach and cooperation between participants operating in the supply chain, from producer to final consumer. It is essential to ensure that every aspect of the product life cycle adheres to guidelines and promotes the overall goal (UN, 2018).

Producing foods requires inputs from various sources such as land, seedlings, water, fertiliser, pest control and harvesting. Each of these primary sources is accompanied by secondary inputs such as energy for irrigation, and harvesting together with production inputs associated with fertilisers and chemicals (Steyn, 2016). To quantify the environmental footprint of production both the primary and secondary inputs need to be considered together with additional upstream and downstream activities as all of the activities associated with production contribute to the final carbon footprint. This is known as life cycle assessment (LCA) which takes into consideration each step that contributes to the final product and the total carbon footprint associated with a product (CleanMetrics, 2018).

Furthermore, the role that the consumer plays has to be included in the calculation. Quality attributes that may influence consumer consumption and purchasing behaviours can have a significant effect on the upstream chain. Therefore, the quality outputs as provided by the agricultural sector need to be explored to ensure that the commodity is not only sustainable from a production perspective, but also from the consumer side.

1.2.3 Nutrient Density and Quality

Nutrition is about more than just kilojoules, however, modern diets are becoming more energy rich and nutrient poor. This change in consumption, together with a general decrease in physical activity are manifested in the increased prevalence of global obesity (WHO, 2018). Studies have shown that the healthy foods are not merely defined by the "healthy" nutrients that they contain, but rather by the absence of ingredients of concern such as fat, sugar and salt. Nutrient profiling ranks foods according to their nutritional composition to promote human health and to prevent disease. These models are being used more frequently for the regulation of nutrient and health claims and more specifically in marketing to children. These regulations aim to protect the consumer against misleading information on food labels, and to inform industry about the contribution their product can make to the diet. The models allow for accurate plotting of nutrient density scores of various foodstuffs on a non-biased scientific basis (WHO, 2011).

Figure 1-4: SDGs that are relevant to nutrition (UN, 2019)

For many years the food industry has stuck by the mantra "*There are no healthy or unhealthy foods, only healthy and unhealthy diets*." Nutrient profiling models have proved this statement wrong, setting the scene for improved cooperation between health professionals and the food industry through accurate product descriptions and comparisons (Wentzel-Viljoen, et al., 2010). This also places the focus on the promotion of high quality nutrients in the diet.

Nutrient-dense foods such as fruits and vegetables are the opposite of energy-dense food which are also referred to as empty kilojoules i.e. beverages and soft drinks including alcohol and foods containing high amounts of added sugar. Nutrient density is not only a unique method to distinguish between different types of food, but also allows for comparison between different cultivars of *Solanum tubersosum L.* or species of the same kinds of food. This can be useful from an agricultural perspective for the promotion of specific cultivars or species (Buttriss, et al., 2014; Darmon, et al., 2005).

Defining a healthy food is complex. Singular nutrients or energy vs nutrient ratios can be difficult to determine, quantify and communicate to policy makers and consumers. Therefore, various approaches are used in an attempt to quantify healthy foods. Even though a standardised concept of healthy foods and how to measure it still needs to be agreed upon and implemented within existing dietary guidelines, nutrient density and nutrient quality of foods in relation to their energy content is a step in the right direction (Drewnowski, 2005).

Various nutrient density models are available to achieve these outcomes. Some of the most popular models include the following:

1.2.3.1 French SAIN/LIM model

The limited nutrient score (LIM) considers three nutrients which should be limited, most commonly saturated fat, added sugar and sodium (Darmon, et al., 2005). The nutrient density score called 'SAIN' (score of nutritional adequacy of individual foods) refers to the nutrient density of a specific food. The SAIN score is an unweighted arithmetic mean of the percentage adequacy for five positive nutrients (plus 1 optional nutrient), which can differ according to specific dietary outcomes. The SAIN score is calculated for 100 kcal of food. The LIM score is the mean percentage of the maximal recommended values for the three nutrients of which the intakes of should be limited in a healthy diet (Table 1-1) (Tharrey, et al., 2017).

Table 1-1: The French SAIN/LIM model

Subscores LIM	Formula	Unit	Explanation
LIM_100 g	$\sum_{1\text{–}3} (L_i/MRV_i) \times 100$	100 g	L_i = content of limiting nutrient *i* in 100g MRV = Maximum Recommended Value
LIM_100 kcal	(LIM_100 g/ED) × 100	100 kcal	ED = Energy Density (kcal/100 g)
LIM_RACC	(LIM_100 g/100) × RACC	Serving	Reference Amounts Customarily Consumed (RACC) = Food and Drug Administrator (FDA) serving size

1.2.3.2 British FSA-Ofcom model

The British FSA-Ofcom nutrient rich (NR) model was one of the first models that was developed to determine nutrient rich foods. This model is implemented by the Food Standards Agency (FSA). This model considers a variety of beneficial nutrients that can be included in the model with no limit (Trichterborn, et al., 2011). The British FSA-Ofcom model (Table 1-2) derives its name from the United Kingdom regulator for the broadcast media know as is the Office of Communications, which is more commonly referred to as Ofcom (Rayner, et al., 2009).

Table 1-2: The British FSA-Ofcom model

Subscores NR*n*	**Formula**	**Unit**	**Explanation**
NR*n*_100 g	$\sum_{1-n}$ (Nutrient$_i$/DV$_i$) × 100	100 g	Nutrient$_i$ = content of nutrient *i* in 100 g DV = Daily Value
NR*n*_100 kcal	(NR*n*_100 g/ED) × 100	100 kcal	ED = Energy Density (kcal/100 g)
NR*n*_RACC	(NR*n*_100 g/100) × RACC	Serving	Reference Amounts Customarily Consumed RACC = FDA serving size

1.2.3.3 NRF 9.3 Index

The Nutrient Rich Food Index (NRF9.3) is based on an arithmetic calculation which takes both the positive (NR) model and the negative (LIM) model into consideration (Table 1-3). The NRF model balances nutrients that should be encouraged, which vary according to country requirements, but are commonly protein, fiber, vitamin A, vitamin C, vitamin E, calcium, iron, magnesium, and potassium, against three nutrients that should be limited (saturated fats, sugars, and sodium), using 100 kcal as the basis of calculation. The NRF9.3 algorithm is the unweighted sum of percentage daily values (DV) for nine nutrients to encourage, minus the sum of percentage maximum recommended values (MRVs) for three nutrients to limit, calculated per reference amount and capped at 100% DV. This model was originally developed by the United States Department of Agriculture and extensively tested and refined by Drewnowski (Drewnowski & Fulgoni, 2008).

Table 1-3: The NRF 9.3 Index

Composite NRF*n*0.3	**Formula**	**Unit**	**Explanation**
NRF*n*.3_sum	NR*n*_100 kcal – LIM_100 kcal	100 kcal	Difference between sums
NRF*n*.3_mean	NR*n*/*n* – LIM/3	100 kcal	Difference between means
NRF*n*.3_ratio	NR*n*/LIM^2	None	Ratio

These models promote various outcomes, while taking into consideration that the energy content of a diet is a very poor measure of its sufficiency, and that a wide set of essential nutrients, including protein, vitamins and minerals, are required as part of healthy, sustainable diets. Therefore, models include various nutrients calculated in numerous ways in order to be aligned with required outcomes. The quantity and more specifically quality of a specific nutrient (nutrient content), such as protein, found in a food forms an important point of departure for arguments related to the role of that specific food in relation to human dietary needs.

Aligning this in the context of emerging areas of research as called for by the joint FAO/WHO Expert Meetings on Nutrition, that was established in 2009 to provide scientific advice to the committees of the Joint FAO/WHO Food Standards Programme or Member Countries, it was that that there is a need for research on the quality of protein food for human health. This research falls under the Committee on Nutrition and Foods for Special Dietary Uses. Both the FAO and WHO encouraged relevant stakeholders to generate more data on the amino acid composition of foods with food group specific calls raised yearly (FAO Nutrition, 2019). Locally, the South African Department of Health has published draft regulations which include a Guideline for protein quality requirements (dependent on amino acids) for labelling and marketing purposes (FAO, 2013).

Protein quality answers two important questions, namely how much protein, as well as what kind of protein, should be consumed? Dietary proteins are classified as either being complete or incomplete. Foods that contain all the indispensable (essential) amino acids are referred to as complete proteins. These are most commonly animal source foods with the inclusion of certain plant based foods. Mostly plant foods lack one or more essential amino acid, which renders these sources of protein "incomplete". Sulphur containing amino acids, such as methionine, cysteine and lysine, most commonly limit the nutritional value (quality) of proteins in the human diet. Concentrations of these amino acids are considered lower in plant foods than in food of animal origin, prompting the need for exploration of plant based foods that can fulfil the role of protein despite the limiting amino acids (Bártová, et al., 2015).

In the South African Food Composition Tables hosted by the Medical Research Council, all available amino acid data is kept in a separate dataset and is generally not freely available as a reference source. Currently, there is no specific South African amino acid data available for potatoes.

Agriculture

The nutrient content of foods and absorption rate of nutrients in the human body have become an intricate science that has gained increasing attention over the last decade. The daily food and drink we consume influence health through the nutrients we consume and, therefore, eventually it determines each individual's quality of life. The most favourable state of nutrition is that of optimal nutrition, and not a mere absence of disease or infirmity (Pretorius, 2018). Due to a surge in population growth and a decrease in arable land, the demand for the production of high nutrient quality crops has escalated. One of the main drivers behind agricultural practise is to produce crops that fulfil the nutritional requirements of humans and animals (Martinez-Ballesta, et al., 2010).

Agricultural practices are the main source of the food supply and, therefore, any changes or events in the field of agriculture will have a direct impact on the food supply and its quality. There are a variety of abiotic factors that have an effect on the nutritional content of agricultural crops for human consumption. Some of the major influencers include water stress (which is of particular concern in arid lands were water is scarce), poor soil conditions (such as soils with a high salt content) and even light intensity which has an effect on the transportation and storage of nutrients in crops. Abiotic factors are usually interrelated which exacerbates the stress experienced by the plant, thus aggravating morphological, physiological, biochemical, and molecular changes that can cause irreparable damage to the plant and thereby directly affect the quality of the tuber, in the case of potatoes (Bita & Gerats, 2013; Eppendorfer & Eggum, 1994).

Sustainable consumption and production is about promoting resource and energy efficiency, sustainable infrastructure, and a better quality of life for all. If conducted in a sustainable manner, agriculture, forestry and fisheries can deliver nutritious food for all and generate liveable incomes, while supporting people-centred rural development and protecting the environment. It also requires a systemic approach and cooperation among actors operating in the supply chain, from producer to consumer. It is important to ensure that every aspect of the product life cycle adheres to guidelines and promotes the overall goal (UN, 2018).

Embodied carbon assessment is a subset of a broader discipline called Life Cycle Assessment (LCA) which covers a range of different environmental impacts. There are various methods to calculate the LCA or total emissions of a product. Table 1-4 lists some of the most common tools used in carbon emission reporting. The goal of the various tools is to allow industries to create quantifiable values for greenhouse gas emission (GHGE) that can be used to create scalable solutions.

Table 1-4: A summary of the most common global carbon emission tools

Aim of user		Calculators
Raising awareness		Carbon Calculator for New Zealand Agriculture and Horticulture (New Zealand), Cplan v.0 (United Kingdom), Farming Enterprise GHG Calculator (Australia), US cropland GHG calculator (United States America).
Reporting	Landscape tools	Agriculture and Land Use National Greenhouse Gas Inventory (ALU) (World), Climagri (France), FullCam (Australia).
	Farm tools	Diaterre (France), Country Land and Business Association (CALM) (United Kingdom), Cool Farm Forum (CFF) Carbon Calculator (United Kingdom), Confronting Climate Change (South Africa).
Project evaluation	Focus on carbon credit schemes	Farmgas (Australia), Carbon Farming tool (New Zealand), Forest tools: Tool for Afforestation and Reforestation Approved Methodologies (TARAM) (World), CO2 fix (World).
	Not focussed on carbon credit schemes	Ex-Ante Carbon-balance Tool (EX-ACT) (World), US AID Farm Carbon Calculator (FCC) (Developing Countries), Carbon Benefits Project (CBP) (World), Holos (Whole-farm Model) (Canada), CAR livestock tools (United States of America).
Market and product orientated tools		**Cool farm tool** (World), Diaterre (France), Confronting Climate Change (South Africa), Life Cycle Assessment (LCA) tools and associated database (SimaPro, ecoinvent, **Clean Metrics Carbon Scope, LCA food** etc.) *

Names in Bold were used in this thesis.

*The principle standards governing the use of LCA are the ISO 14040 series of standards. These provide guidance on (BSI, 2006):

- LCA principles and framework ISO 14040
- LCA requirements and guidelines ISO 14044

1.2.4 Consumers

In South Africa consumption and food expenditure vary across different market segments. The South African consumer is divided into four expenditure deciles i.e. marginalised, lower middle-income, upper middle-income and upper income. Income and expenditure vary over these groups, together with the types of products they expend it on. The marginalised and lower middle-income groups spend the biggest portion of their food expenditure on staple foods. Of these staple foods, the dominant staple foods in order of importance are maize meal, brown bread, rice, white bread and potatoes (Figure 1-1). On the other end of the spectrum, the wealthiest consumers have different preferences for staple foods, presented here in descending order of importance; brown bread, white bread, rice, maize meal and potatoes (StatsSA, 2016; StatsSA, 2010/2011). Most of the South African potato crop is consumed by lower income groups i.e. the marginalised (30%) and lower middle-income group (30%), which is the largest group in South Africa. Furthermore more than half of the crop (53%) is utilized by informal processors, followed by formal trade (31%), processors (8%) and finally exports (7%), which are most commonly to neighbouring countries (Potatoes South Africa, 2017).

Food affordability is one of the main concerns for South African consumers and guides many food choices. Of the 80-85% of their total food expenditure that marginalised consumers spend on staple foods only 8.4% is spend on potatoes. However, apart from a decline in potato consumption in 2009 and 2016, due to a recession and crop losses respectively, a steady increase is seen in potato consumption over the past 20 years leaving stakeholders optimistic about the future potential of the product as a staple, as well as a food security crop in South Africa (BFAP, 2019).

1.2.5 Regulatory environment

Governments play an essential role in creating and enabling sustainable, safe and effective food environments that support food safety and security outcomes. The food regulatory environment impacts the foods that are most available (economical), the nutritional quality (social), and the way in which food is produced (environmental). These factors have far reaching consequences in terms of the choices that the consumer have and make (Evensen, 2014). This is achieved through various forms of legislation that were put in place to protect both the consumer and the producer by means of honest communication through labelling, marketing and production.

The South African food legislative environment consists of various laws that are enforced by different departments and institutions. For the purpose of this thesis only the legislation that is relevant to the outcomes of this study will be discussed. However, it is important to note that there are far wider reaching laws that influence the food system at large.

Greenhouse gas emission

Internationally, pressure is exerted on food production systems to implement more sustainable methods of production, such as reductions in the utilization of natural resources. To ensure that local government aligns regulatory and food outcomes with international agendas, the South African Cabinet approved the National Climate Change Response White Paper in 2011. The first draft of the Carbon Tax Bill was published for public comment in November 2015. In 2018 it was stated that the actual date of implementation of the carbon tax will be determined via a separate and later process by the Minister of Finance through an announcement during 2018, or during the Budget Speech in 2019, taking into account the state of the economy. Due to a greater focus on the breakdown of state owned enterprises in 2019, an initial carbon tax of 9c on fuel was put in place as of 2019 with further inclusions to be added in coming years. However, this carbon tax on fuel does not go towards funding 'green' projects, but is currently redirected towards the national budget rendering the tax irrelevant to sustainability outcomes (South African Government, 2019).

Even though the exact extent of the looming carbon tax for South Africa is unknown, the production sector needs to start the process of measuring and plotting the carbon emissions of different industries and attempt to find viable options to reduce carbon emissions. Such legislation will have a downstream effect that may affect price and availability of foods and, therefore, sustainable diets need to be taken into consideration to ensure a rapidly growing population can be nutritionally sustained.

Labelling

The South African National Department of Health implemented the Foodstuffs, Cosmetics and Disinfectant Act (ACT 54 of 1972) to "*control the sale, manufacture and importation of foodstuffs, cosmetics and disinfectants and to provide for incidental matters"*. The relevance of this act to the present study is stipulated in the recently amended section of the Act relating to protein, that now states that no protein claim may be made for a food, if the food does not contain at least a certain quantity of each of the amino acids listed in the regulations. It is, therefore, required that amino acid content data be available for all food products that want to make protein content or functional claims (Department of Health, 2014).

Apart from nutrient classification, there is also product specific classification. The classification of foods within a system is a complex process that is unique to each specific product group and class. The South African potato classification system, as developed in 2011, classifies potatoes into three categories, waxy, waxy/floury and floury. Even though this form of category classification is not a legal requirement, it is a guide for the consumer when making purchasing decisions. According to the Agricultural Products Standards Act No.199 of 1990 on potato sales, the cultivar needs to be indicated clearly on the packaging of all potatoes sold on the market allowing consumers to make an informed decision at point of sale (Department of Agriculture Forestry and Fishery, 2010). This legislation is, however, not well enforced.

1.3 Justification of the study

The South African potato industry has responded to issues of sustainability, agricultural changes and consumer needs through the implementation of dedicated research studies that address and promote change in these fields. In order that the South African potato industry can be aligned with sustainability goals, as stipulated in local and international policies, programmes and regulations, in a manner that is in line with dominant social norms, behaviours, governance and management regimes, research is required (Pereira, et al., 2015). To ensure that these discussions are informed by science based evidence, various research studies have been completed or are currently underway. These studies aim to improve the production efficiency of the South African potato sector ensuring a sustainable crop for generations to come (Steyn, 2016).

The growing world population dictates that future food policies and production action plans need to incorporate sustainability goals to ensure that 9.7 billion people can be fed nutritious food sourced from limited arable land (UN, 2018). As potatoes and their derivatives play a significant role in the global food industry they are a crop of particular interest, therefore, all the role players that contribute and gain from this sector are obliged to further investigate and extrapolate data to ensure sustainable development of the industry within South Africa.

South Africa experienced economic growth during a nutrition transition. Individuals are increasingly becoming financially capable of purchasing from multinational low-priced food chains which has led to an increase in the consumption of energy-dense , nutrient poor, processed foods which is seen as a powerful driver of dietary changes (Steyn & Mchiza, 2014). These dietary changes influence both the health and agricultural landscape which is also directly linked to sustainability.

Even though South Africa is currently classified as a food secure nation at national level there are major gaps in nutrition security. Previous studies on food security focused on energy requirements and not on nutritional requirements and quality. As there are many external factors that have an effect on nutritional outcomes, it may sometimes be a challenge to ensure the right intervention is chosen to solve a specific dilemma. Greater emphasis is being placed on the role of specific high quality nutrients rather than focusing on producing vast amounts of empty kilojoules (EAT-Lancet , 2019).

Several drivers are emerging, that may radically affect the development of global food systems. An agricultural-based approach for overcoming malnutrition and improving nutrition in general can be implemented as an action plan especially in developing countries. The synergy that exists between nutrition and agriculture can play a fundamental role in alleviating hunger, raising levels of nutrition and ensuring freedom from hunger and malnutrition by promoting sustainable agricultural development at an area-specific level (Thompson & Amoroso, 2011).

As the modern food and agricultural system is often the culprit in the health and nutritional status of a population, addressing the problem at grassroots level may ensure a positive downstream effect. Good nutrition depends to a large extent on the agricultural landscape. Foods that are produced at whatever level, directly contribute ~~s~~ to health outcomes and can either relieve or aggravate nutritional status (Thomas, et al., 2015). To ensure that industry equilibrium is achieved stakeholders from the various fields in the system need to collaborate to attain this goal of sustainable nutrient sensitive agriculture.

Globally guidelines are being developed that aim to nurture human health while supporting environmental sustainability. Such guidelines are urgently required to address the rapidly changing food system, that is necessary to support population growth. Guidelines that aim at achieving sustainable action-based outcomes, include the Sustainable Development Goals, as well as the Paris agreement, both set in action by the United Nations. In general, both of these action ~~s~~ plans aim at responding to the global threat of climate change through various intervention strategies (UN, 2019).

As 70% of the Sustainable Development Goals contain nutrition related indicators, it is important to realise what a cardinal role food and nutrition play in sustainability. Attaining the SDGs could mobilize further investment to understand the complexity of food value chains and their predicted outcomes, linked to improved nutrition and sustainability. Furthermore the goals promote synergy between different industries and envisions that through this approach valuable insight can be gained to ensure the creation of a better world for all (UNDP, 2019).

A growing body of scientific evidence reveals the intricate relationships between food intake, food affordability, public health nutrition, food security and the environment (e.g. Heller et al. (2013), O'Kane (2012), Tilman & Clark (2014), Berry et al. (2015), Clonan & Holdsworth (2012), Donini et al. (2016)). Therefore, country specific research is needed to relieve the global burden of malnutrition. The World Health Organization states that "*malnutrition is one of the greatest challenges of our time, affecting at least one in three people*". It is estimated that 815 million people are chronically undernourished, while a further 1.9 billion adults are either overweight or obese. More alarming is the rate of children being affected; reaching percentages of 22.2% of children under 5 years of age being stunted and 7.5% wasted as a result of hunger and malnutrition (WHO/NHD, 2019). Finding local solutions form the basis of addressing this global issue. It provides timely opportunities for specific sectors to initiate and accelerate research that not only improves the industry and commodity at a local level but also contributes to the global scalable planetary boundaries.

In this thesis potatoes were chosen as a commodity for further exploration regarding their role in a sustainable nutritious food system. Potatoes are the most important non-cereal food crop in the world and comprise a significant part of the global agricultural sector (Juyo, et al., 2018). In 2019 South African potato production reached 2.45 million tons from 52 0117 ha of land. This increase in yield and production capacity can be directly linked to the introduction of improved cultivation practices (Potatoes South Africa, 2019; BFAP, 2017). This crop accounts for approximately 45% of the total quantity of vegetables produced in South Africa and 14% of total plant production. Potatoes also account for 4% of total agricultural production in the country contributing more than US$0.6 billion to the GDP (BFAP, 2019; Ngobese & Workneh, 2016). However total contribution to plant production is still lower than that seen in America at 15% (USDA, 2015) and higher than the levels seen in the related BRICS (Brazil, Russia, India, China and South Africa) country Brazil, where large scale potato production is in a growth phase (IDAL, 2016).

Not only does this sector contribute to the local economy, but it can play a bilateral role in the nutrition and sustainability context. Potatoes can produce more food per unit of water than other major staple crops. Tubers also contribute significant amounts of essential nutrients to the diet and deliver more energy and edible biomass per hectare cultivated than its staple counterparts such as maize, wheat and rice (Narvaez-Cuenca, et al., 2018).

This thesis will aim to address these issues by means of six different chapters. Based on the EAT-Lancet Report nutrient-dense high quality plant based products have a significant role to play in the diet and food-system outcomes (EAT-Lancet , 2019). In line with this, sustainable country goals consistent with country-specific culture need to be identified, investigated and addressed. The importance of such research in South Africa is evident from the general notice posted in the Government Gazette on the national greenhouse gas emission reporting regulations that commodity specific actions need to be taken in order to be aligned with international targets for the reduction of greenhouse gas emission (Department Environmental Affairs, 2017) (**Chapter 2**). From a local nutrition perspective, accurate information on nutrient content data is required that can address the contribution that potatoes can make to a high quality diet within a sustainable food system. (**Chapter 3**). The changing agricultural and consumer landscape may have a significant effect on the final product and how it is perceived by the consumer. Therefore, it is necessary to investigate the effect that these changes have on the quality of the final product in an agriculturally diverse landscape such as South Africa. Exploring and understanding the area specific internal characteristics of tubers is necessary for optimal production of a crop **(Chapter 4)**. Furthermore, in order to embrace the diversity of the commodity, a classification system is required that classifies potatoes based on their unique internal characteristics in a scientific manner (**Chapter 5**). In addition to a scientific based method, a validated, repeatable and reliable “on farm” method for classification is required that can classify potatoes on a batch specific level (**Chapter 6**). In **Chapter 7** the contents of the various articles are summarised to provide a constructive argument pertaining to the role of potatoes within the three pillars of sustainability: agriculture, sustainability and the nutrition matrix in the South African context.

Ethical clearance (EC170501-123) was granted by the University of Pretoria ethical comity at the start of this project and is shown in Appendix A.

1.4 Aim and objectives

The aim of the thesis is to investigate the sustainability of staple food consumption in South Africa from a human nutrition perspective with emphasis on the South African potato sector while considering agricultural effects on internal quality aspects.

The objectives are:

1. To develop a sustainability index for the South African potato sector.
2. To build a case for potatoes as a high quality protein source that can inform dietary choices and assist in consumer education programmes.
3. To determine the effect of external conditions on the internal properties of potatoes.
4. To evaluate classification methods of internal properties that have a significant effect on the textural properties of potatoes.
5. To develop a farm level tool for the classification of potatoes.

1.5 Structure of the thesis

The structure and outline of the thesis is as follows:

Chapter 1: The study in perspective

An overview of the study was provided in this chapter.

Chapter 2: Development of a sustainability index for the South African potato sector

A sustainability index was developed for potatoes within the South African context using a nutrient density model together with GHGE scores.

Chapter 3: Protein quality of South African potatoes to inform dietary choices

Potatoes can play a significant role in the diet as a high nutrient quality starch based staple food. As the world population is growing exponentially there is a demand for more protein as an essential macronutrient. This need is in turn increasing the need to quantify and define the amount and quality of protein contained in specific foodstuffs. Protein content and amino acid content were determined for four varieties of the most commonly consumed potato tubers in South Africa.

Chapter 4: The effect of external conditions on the internal qualities of potatoes

A country wide study was conducted sourcing tubers from various experimental plots to investigate the external factors that have an effect on internal quality attributes.

Chapter 5: The reliability of dry matter, specific gravity, starch and glycaemic index in the classification of potatoes

Potatoes are classified using an array of methods. In this chapter the effectiveness of different classification methods was investigated.

Chapter 6: Development of a farm level tool for potato classification

As potatoes are a non-homogenous agricultural commodity, various internal and external factors influence their internal textural characteristics. These textural differences observed between cultivars elicit batch-specific cooking qualities which are difficult to predict prior to cooking. Therefore, new and innovative potato classification methods are constantly being developed in an attempt to successfully classify potatoes based on internal textural qualities. Subsequently, a need was identified for a batch-specific classification method to classify potatoes in a reliable and repeatable manner at farm level with minimum equipment and cost.

Chapter 7: Conclusions, recommendations and lessons learned

The final chapter summarises the main findings of the research described in the previous chapters. The implications of these findings and recommendations to consider in the future are presented and discussed. The lessons learned and challenges faced in the execution of this thesis are discussed.

This thesis provides scientific information on the effect of production practices on tubers and consequently the effect this has on classification. It explores the role of potatoes as a nutrient dense sustainable crop in the context of the South African staple food domain.

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Chapter 2: Exploring nutrient density as an indicator of sustainability: A South African case study with a focus on potatoes

"The greatest threat to our planet is the belief that someone else will save it." – Robert Swan

Abstract

It is becoming increasingly important to consider concerns about nutrient density (ND) in relation to environmental impact. To develop a strong quantifiable case for potatoes, a project was proposed to mathematically evaluate the nutrient density of South African potato products and staple foods in relation to their carbon footprint and water usage. This project proposed to merge greenhouse gas emissions (GHGE's) of specific food products with nutrient composition data for those foods. Nutrient density scores were calculated and linked to GHGE's and embodied water values and plotted.

Potatoes proved to have the highest ND score associated with lowest GHGE values of the most commonly consumed staple foods (maize meal, bread, pasta and rice). Furthermore, it was found that potatoes had the lowest embodied water value per unit nutrient density indicating that potatoes are extremely water efficient in terms of nutrients delivered when compared to the most commonly consumed staple foods.

2.1 Introduction

Addressing and overcoming issues of sustainability require a systemic approach and cooperation among participants operating in the supply chain, from producer to final consumer. A projected world population of 9.5 billion people by 2050 dictates that future food-related policies must support a sustainable food system. To support this statement, there is an urgent need to define recommendations and actions which are high on the international agenda. Consequently, a new set of Sustainable Development Goals have been implemented in an attempt to ensure improved quality of life for all.

Continual growth of human influences on the environment contributes significantly to climate change which poses a threat to the environment and its inhabitants (WHO, 2018). The agricultural sector is often under the spotlight in these sustainability discussions. Thus this sector has an historic opportunity to become more involved in shaping the definition of sustainable food systems and healthy, sustainable food baskets that can feed the future populations in a sustainable and nutritional manner. Such actions aim at "doing more and better with less," while increasing quality of life for all through policies and programmes.

Governments around the world are aiming to implement such policies to promote healthier sustainable diets. These fairly ambitious plans which fundamentally aim to provide the growing population with affordable, acceptable, healthy diverse food whilst taking environmental concerns into account require a multispectral approach. Solutions to these issues require action plans that need to be coordinated at a global level together with international buy-in. However, at the root of the problem it needs to be addressed at a country specific level and even more specifically at an industry specific level (Lee, et al., 2013).

In many developing countries, undernutrition persists in the midst of overweight and obesity. There is, therefore, an increased focus on nutrient quality food security debates. Nutrient quality can be measured in terms of nutrient density, and specifically nutrient density and its environmental impact on local food systems. Nutrient density is determined using various methods that show the nutritional value in terms of energy of a specific food. Considering the food basket, the inclusion of staple foods offers a unique opportunity, as they are affordable, culturally acceptable, readily available and usually have a relatively long shelf-life (Sibhatu & Qaim, 2017).

Staple crops are major role-players in diets throughout developing countries as is the case of Sub-Saharan Africa. In low income countries 3% of total dietary energy, as an indicator of diet composition, is derived from meat and offal, 11% from roots and tubers and 6% from pulses, nuts and oilseeds. The remainder of the dietary energy is mainly derived from cereal-based staple food. Staple food consumption plays a cardinal role in the diets of these populations contributing significantly to their energy and nutrient intake (Schönfeldt & Hall, 2012). Even though undernutrition remains a persistent problem in the developing world; environmental concerns of intensified agriculture cannot be ignored.

Redesigning the food system to enhance nutritional benefits while limiting damage to the environment should, therefore, be a topic for serious consideration pertaining to staple foods. By promoting staple foods that are nutrient dense while simultaneously delivering a smaller carbon footprint not only promotes nutrient dense diets, but also sustainable living.

Dominant staple foods in South Africa as presented in Table 2-1 are maize meal, brown bread, rice, white bread and potatoes. These staples are a source of macro- and micronutrients and as stated in the Food-Based Dietary Guidelines (FBDG) they should form the bases of most meals. This paper is mainly focussed on potatoes with reference to other staples.

2.2 Justification

Sustainable consumption and production is about promoting resource and energy efficiency, sustainable infrastructure, and a better quality of life for all. If conducted in a sustainable manner, agriculture, forestry and fisheries can deliver nutritious food for all and generate liveable incomes, while supporting people-centred rural development and protecting the environment. It also requires a systemic approach and cooperation among role-players in the supply chain, from producer to final consumer. Ensuring that every aspect of the product life cycle adheres to its guidelines and promotes the overall goal can only be achieved by careful planning and cooperation (UN, 2018).

2.3 Objective

Determining the nutrient density of staple foods in a sustainability context.

2.4 Methodology

Comparisons between different food production systems are notoriously complex with this research revealing a pronounced variability between different ways of producing the same food. Some of the more extreme findings report significant differences in values observed over varying farming systems and consequently differences between countries making each countries production system unique. Therefore, the proposed project was done on common production practices followed in South Africa together with nutrient content values of staple foods determined in this country.

Summary of methodology:

Phase 1: Determine the nutrient density of commonly consumed foods in Sub-Saharan Africa.

a. Identify the most commonly consumed staple foods

b. Source food composition data for these foods

c. Review nutrient profiling models

d. Calculate nutrient density scores

Phase 2: Adapt and apply the Nutrient Density Scores to Climate Impact (NDCI) index

a. Obtain greenhouse gas emission (GHGE) values

b. Plot nutrient density scores against GHGE

2.4.1 Nutrient density

A desktop review was conducted on the foods most commonly consumed in South Africa, using resources and data obtained from food balance sheets as well as food intake surveys conducted at a national level, as well as smaller studies carried out in specific communities (Vermeulen, et al., 2015; Mchiza, et al., 2015; Labadarios, et al., 2011). Table 2-1 shows the total share of expenditure on five of the main staple foods as consumed in South Africa. A total number of n=25 foods were identified from all the different food groups. The staple foods that clearly overlap in the various studies were used in the final staple food list (Table 2-2). These staple foods were plotted in an Excel spread sheet database and nutrition data was sourced using the South African Food Composition Tables (Table 2-2) (Wolmarans, et al., 2010).

Table 2-1: Overview of the top staple foods making the largest contribution to food expenditure in South Africa (Vermeulen, et al., 2015)

	% Share of food expenditure
Maize meal	5.9
Brown bread	5.3
Rice	3.5
White bread	3.4
Potatoes	2.1

Table 2-2: Nutritional values used to calculate nutrient density of the identified staple foods (Wolmarans, et al., 2010)

	Protein (g/100g)	Fibre (g/100g)	Vitamin A (ugRE/100g)	Iron (mg/100g)	Calcium (mg/100g)	Vitamin C (mg/100g)	Potassium (mg/100g)	Magnesium (mg/100g)	Zinc (mg/100g)	Saturated fat (g/100g)	Added sugar (g/100g)	Sodium (mg/100g)
Potato	1.5	1.5	0	1.2	6	27	398	15	0.29	0.03	0	2
Maize Meal	7.6	4.1	184	2.6	5	0	98	38	2.07	0.2	0	3
Brown Bread	9	5.5	84	4.1	14	0	227	44	4.49	0.25	0	648
White Bread	8.8	3.2	109	3.6	16	0	214	43	2.15	0.24	0	653
Wheat flour	8.2	1.7	0	1.2	14	0	105	16	0.62	0.13	0	2
Pasta	4.8	1.6	0	0.5	7	0	31	18	0.53	0.1	0	1
Rice	2.7	0.4	0	0.2	11	0	39	13	0.46	0.08	0	2

The nutrient density model NRF 9.3 as developed by Drewnowski and Fulgoni was chosen for this study as the most relevant to the outcome of the study (Fulgoni, et al., 2009; Drewnowski & Fulgoni, 2008). Table 2-3 shows the nutrients used in the nutrient density models. Nutrient density score is calculated as the sum of the percentage of recommended dietary allowance (RDA) for nine nutrients to encourage, minus the sum of the percentage of maximum recommended values for three nutrients to limit (Eq. 1). It was found that these nutrients provide the most accurate ND scores using nutrients that play a significant role in the diet. Nutrient density (ND) was calculated per unit of energy (Buchner, et al., 2010).

$$Nutrient\ Density\ Score = \frac{\left(\sum_{i-9}\left(\frac{X_{1-9}}{RDA_{1-9}}\right) - \sum_{j-3}\left(\frac{Y_{10-12}}{RDA_{10-12}}\right)\right)}{\left(\frac{kJ}{RDA_{kJ}}\right)} \quad \text{(Eq. 1)}$$

Equation to determine the ND score of food products using nutrients as shown in Table 2-2.

Higher ND scores represent higher nutrient density values likewise with GHGE (Doran-Browne, et al., 2015). Nutrient density scores were calculated based on the recommended dietary intakes of nutrients and energy as recommended for various groups of the population. Values were calculated for an 8500kJ diet, which is recommend for an adult, and are presented per 100g product.

Table 2-3: Nutrients used to calculate nutrient density scores

Nutrients used to calculate nutrient density scores	
Nutrients to encourage	**Nutrients to limit**
Protein	Saturated fat
Fibre	Added sugars
Vitamin A	Sodium
Iron	
Calcium	
Vitamin C	
Potassium	
Magnesium	
Zinc*	

*Drewnowski et al., 2008 included vitamin E as the 9th nutrient to encourage, whereas in developing countries in sub-Saharan Africa, zinc is of increasing concern, while limited attention is given to vitamin E in dietary guidelines (Kumssa, et al., 2015). In the current study vitamin E was, therefore, replaced with zinc.

2.4.2 Greenhouse gas emissions

Producing foods requires inputs from various sources such as land, water, fertiliser, pest control and harvesting. Each of these primary sources is accompanied by secondary inputs such as energy for irrigation, and harvesting together with production inputs associated with fertilisers and chemicals (Steyn, 2016). To quantify the environmental footprint of production both the primary and secondary inputs need to be considered together with further up- and downstream activities, because all the activities associated with production contribute to the final carbon footprint.

Greenhouse gas emissions were calculated using the Clean Metrics Food Carbon Scope as it is the most relevant tool for the outcome required. Food Carbon Scope™ complies with applicable international standards (ISO 14040 series, PAS 2050, GHG Protocol) for life cycle assessment (LCA) and product carbon footprint analysis, and is constantly updated to ensure compliance with international standards.

The Clean Metrics Food Carbon Scope accounts for the carbon footprint of a food product or service for the total amount of carbon dioxide (CO_2) and other greenhouse gases emitted over the life-cycle of that product or service, expressed as kilograms of CO_2 equivalents. This includes all greenhouse gases generated in the agricultural phase including emissions from the production and transport of all inputs, as well as emissions due to on-farm energy use and non-energy-related emissions from soils and livestock. The carbon footprint also includes the greenhouse gas emissions generated in the processing and packaging of food products, and delivery to a point of sale or use location. This tool also allows for embodied water calculations on food and beverages showing the total amount of water that was used throughout production of the final product (CleanMetrics, 2018).

Carbon dioxide emission values (Embodied Carbon) for the identified list of foods were obtained from the global Food Carbon Scope databank (Table 2-3). These values were obtained using all available data from production through processing to final consumption.

2.4.3 Area specific production and cultivar related GHGE vs ND

Potato production occurs in many (n=16) distinct geographical areas throughout South Africa. These regions differ in climate, soil, production season and management practices. All of these differing factors affect the amount and input of resources required to produce potatoes, as well as yield and crop value. The input resources used to produce a crop contribute to a crop's total carbon emission, also known as the carbon footprint.

An extensive study on inputs in different production regions was conducted on 106 farms distributed over the 16 South African production regions. Data gathered from this survey were exported into the Cool Farm Tool analytical programme, which provides accurate GHGE values over the chain in the 16 different production regions and is presented as GHGE kg CO_2 eq./ton fresh (Steyn, 2016). In this study, values were plotted against the calculated nutrient density scores of the tubers that are most commonly produced in each specific region. Due to low response rates in the South Western Cape this area was excluded from the study.

2.5 Results and discussions

2.5.1 Staple crops

Potatoes are physiologically classified as a vegetable containing a variety of vitamins and minerals that are essential to the diet (Pennington & Fisher, 2009). Potatoes are the only food on the list of staple foods (Table 2-1) that can be cooked and served *"as is"* post-harvest, with no additions in the form of sugar, fat and salt used during preparation. Sugar, fat and salt are classified as nutrients to limit in the NRF 9.3 model and their presence in food can significantly decrease its ND score (Table 2-4).

Table 2-4 shows the ND scores per 100g raw product of the most commonly consumed staple crops in South Africa. Potatoes scored the highest ND score at 18.79 followed by brown bread at 9.73. Wheat flour and rice had the lowest ND scores at 2.86 and 2.94 respectively. Such interpretive data shows that these nutrient dense tubers can play a significant role in the development of healthy, sustainable dietary recommendations while finding a balance in the greenhouse gas emission vs nutrient density matrix.

As seen in Table 2-4, potatoes had the lowest embodied carbon score per 100g of product when compared to the other staple foods. The longer and more complicated post-harvest processes that are required to transform the other staple foods into their consumable state contribute to increased GHGE scores.

In Figure 2-1, GHGE of the most commonly consumed staple foods are expressed per unit ND. Potatoes had the lowest GHGE per ND score. This means that potatoes are the staple crop that provides the highest ND value for the lowest GHGE value. The most commonly consumed staple food in South Africa, namely maize meal, had the second lowest GHGE score per unit of ND. Rice had the highest GHGE per unit ND supplied.

The growing population ensures that food demands will change. One of the expected and already occurring changes is the need for food of high nutrient quality rather than with a high energy value. This need is driven both by environmental concerns as well as changes in the fiscal ability of consumers in economically growing environments.

In Figure 2-2, the nutrient density scores of the most commonly consumed foods in South Africa are compared to their greenhouse gas emission data. Rice had the highest GHGE score with a low ND score. Potatoes had the lowest GHGE score as well as the highest ND score.

Figure 2-3, shows the energy (kJ) values of the most commonly consumed staple foods in South Africa compared to their greenhouse gas emission data. Rice, pasta and wheat had similar kJ values per-100g portion with varying GHGE scores. Potatoes had the lowest GHGE and energy score.

Table 2-4: Nutrient density, protein, embodied water and embodied carbon values of the most commonly consumed staple crops in South Africa

	ND/100g	kJ/100g	Embodied water/1kg	GHGE/1kg
Potatoes (raw, flesh and skin)	18.79	325	1.10	0.33
Maize meal	7.24	852	8.06	0.63
Brown bread	9.73	1029	5.26	0.83
White bread	6.48	1036	5.26	0.83
Wheat flour	2.86	1499	7.99	0.65
Pasta (raw)	5.07	1552	9.06	1.24
Rice (raw)	2.94	1527	34.29	1.53

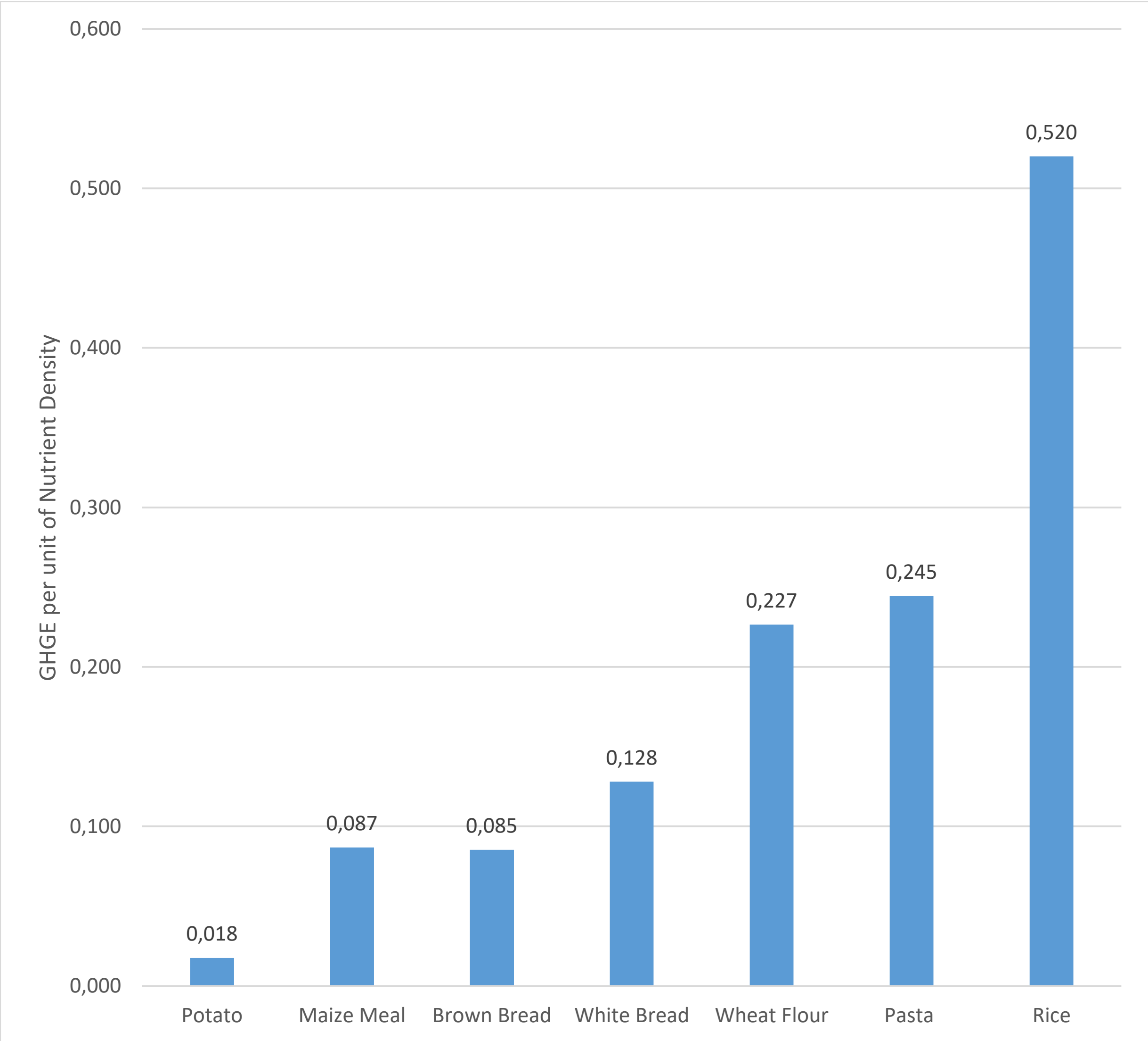

Figure 2-1: Greenhouse gas emission expressed per unit of nutrient density of commonly consumed staple foods in South Africa

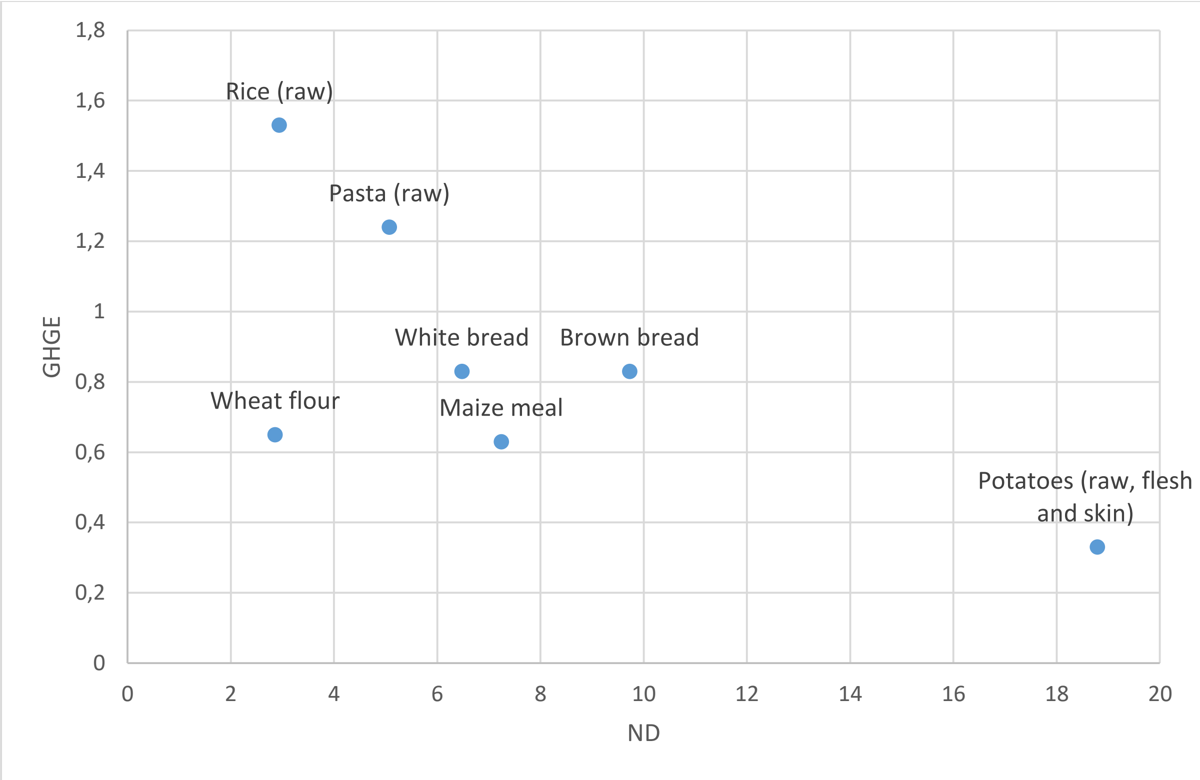

Figure 2-2: Nutrient density scores of the most commonly consumed foods in South Africa compared to their greenhouse gas emission data

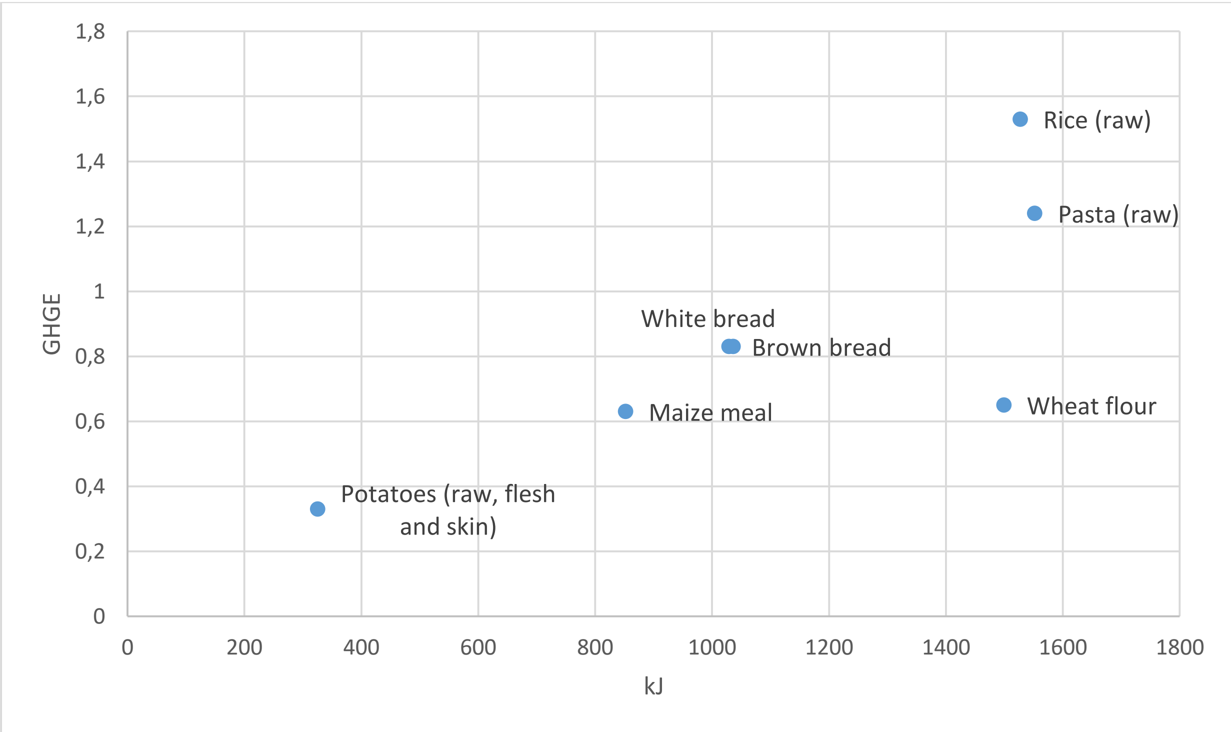

Figure 2-3: Energy (kJ) values of the most commonly consumed staple foods in South Africa compared to their greenhouse gas emission data

2.5.2 Embodied water versus ND of the most commonly consumed staple crops in South Africa

Water is the main source of life without which very little can be achieved. Rapid population growth with the associated need to produce more food exacerbates water scarcity, which is further compounded by a changing climate (FAO, FSN, 2018). One of the greatest uncertainties associated with climate change is the expected reduction in precipitation (Blom-Zandstra & Verhagen, 2015).

These future projections paint a bleak picture for palatable water availability and emphasise the need for sustainable water use. Some of the proposed methods of addressing this persisting issue are the cultivation of water-use-efficient crops in an effort to reduce water scarcity in agriculture (Mohtar & Lawford, 2016). Potatoes are estimated to use only 1% of the total water used for agriculture. This is similar to sugar beet and rape seed and lower than the 18% used by wheat and 13% by maize (Mekonnen & Hoekstra, 2011).

Modern potato varieties are sensitive to soil water deficits and need frequent, shallow irrigation. A 120 to 150 day potato crop consumes from 500 to 700 mm of water. Depletion of the total available soil water during the growing period by more than 50% can result in lower yields.

To apply these findings to the South African context, a ND water uses nexus had to be developed for the most commonly consume staple crops in South Africa. This nexus can be used to inform policy and programmes as to which crops are the most efficient in relation to water-use that should be planted to deliver nutrient dense crops.

Table 2-4 shows the ND scores and embodied water scores for the most commonly consumed staple crops in South Africa. These are the values that are also used in graphs in this section. Embodied water is also known as virtual water trade, which refers to the hidden flow of water that occurs when food or other commodities are traded from one place to another. This is usually expressed as litres of water needed to produce a crop.

The proposed nexus is plotted in Figure 2-5. Embodied water is plotted against the ND scores of the relevant food (Figure 2-4). Rice had the highest water use per ND unit. Pasta (90.62), wheat flour (79.9) and maize meal (86.07) had the highest embodied water scores. Potatoes had the lowest embodied water scores and the highest ND scores of all the staple foods. Potatoes had the lowest water usage per unit ND delivered and rice the highest water usage per ND unit. This is similar to a study conducted by the Food and Agricultural Organization in 2008, which found that potatoes deliver more energy (cal) per litre of water used, than any other staple crop. Not only do potatoes provide more nutrients per unit of water used, but they also produce more energy than rice, wheat and maize per litre of water used (FAO, 2008).

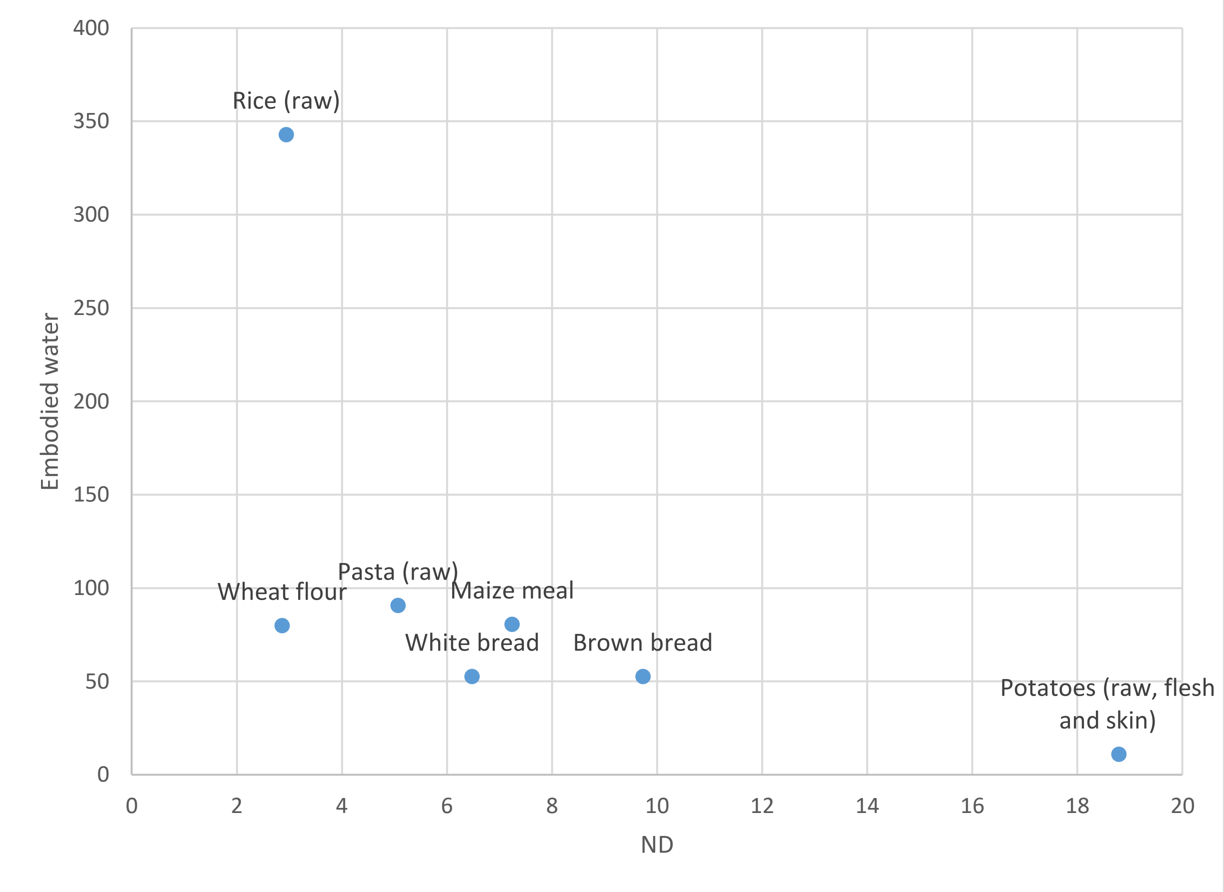

Figure 2-4: Nutrient density values of the most commonly consumed staple foods in South Africa compared to their embodied water values

2.5.3 Region specific

South Africa has a diverse potato producing landscape with tubers being cultivated in 16 different production regions spread all over the country. The unique South Africa landscape lends itself to production of potatoes running seamlessly throughout the winter and summer in different regions. Furthermore, due to rain fed-agriculture in some of the regions, potatoes are cultivated on dry land and under irrigation in South Africa.

Potato production regions are spread over vastly differing climatic regions. These regions vary from Mediterranean climate in the south-western corner of the country to temperate areas to the interior plateau and subtropical climate in the northeast with a small part classified as desert in the northwest of the country. These varying climatic conditions solicit area specific agricultural applications. The variance in input resources leads to differing GHGE outputs over the regions. Furthermore, certain cultivars are more commonly produced in certain regions. Therefore, the ND of the most commonly produced tubers was calculated for each region and plotted against the GHGE of that specific region as obtained from a study conducted by Steyn (2016). Data for this study is expressed in kg CO_2/ton as obtained from the Cool Farm Tool used in the study. All the plots were irrigated to some extent during the course of the planting season depending on precipitation.

As see in Table 2-5, the Eastern Free State had the lowest GHGE score together with the highest ND score for Mondial, which is the most commonly produced cultivar in that region. Gauteng and Sandveld had similar high values for GHGE as well as high ND values for the most commonly produced cultivars Mondial and Sifra respectively. Fianna, which is mostly produced in the Mpumalanga Highveld (HV) region and Ceres, has a lower ND score with Mpumalanga Highveld receiving a low GHGE score and Ceres a high GHGE score. The Southern Cape had low scores for both GHGE and ND for the cultivar BP1. Sifra, which is the most commonly produced crop in Mpumalanga, the Northern Cape, North West, South West Free State and Sandveld, scored a moderate to high ND value, while GHGE differed between these regions.

Table 2-5: The 16 different potato production regions in South Africa and the most commonly produced cultivar in each region

Region	Abbreviation	kg CO_2/ton (GHGE)	Nutrient Density	Cultivar
Eastern Free State	EFS	138	18.35	Mondial
Eastern Cape	EC	243	18.35	Mondial
North Eastern Cape	NEC	203	18.35	Mondial
Kwa-Zulu Natal	KZN	204	18.35	Mondial
Mpumalanga	MH	215	17.84	Sifra
Northern Cape	NC	238	17.84	Sifra
Southern Cape	SC	168	16.36	BP1
Gauteng	GT	324	18.35	Mondial
Sandveld	SAND	329	17.84	Sifra
Limpopo	LIM	300	18.35	Mondial
Ceres	CERES	281	16.90	Fianna
Western Free State	WFS	216	18.35	Mondial
South Western Free State	SWFS	265	17.84	Sifra
North West	NW	248	17.84	Sifra
Mpumalanga Highveld	HV	160	16.90	Fianna

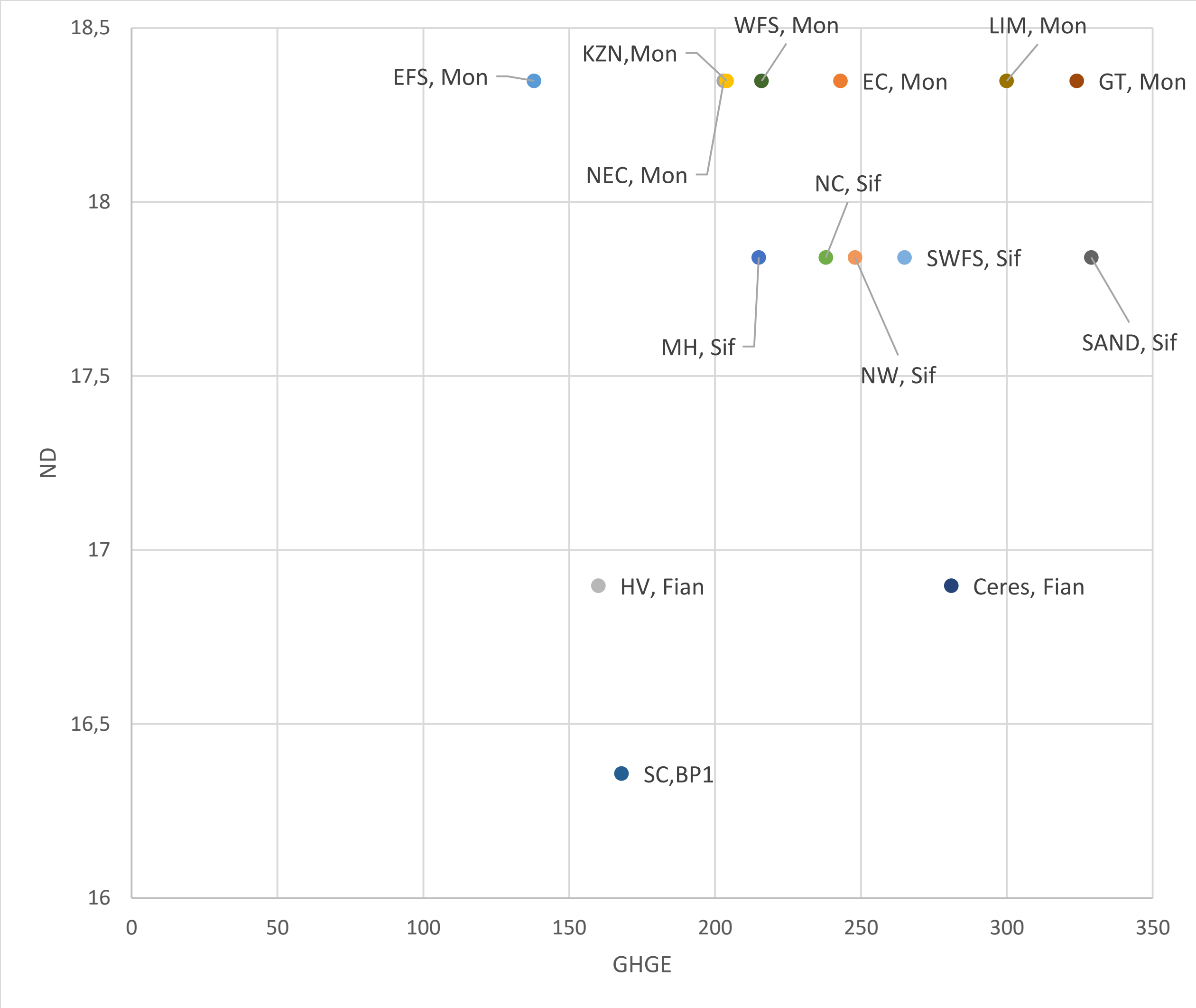

Figure 2-5: GHGE versus ND over specific regions and for most commonly consumed cultivar

2.6 Conclusions and recommendations

The sustainable diet concept acts as a point of departure for enforcing policies and programmes to ensure food security for future generations. In order to guide these decisions, the contribution of dietary choices to the carbon footprint needs to be measured. Evaluating the carbon emission contribution of staple foods in Sub-Saharan Africa provides a baseline for dietary recommendations.

The premise of this study is based on the hypothesis that minimally processed potatoes would have a low carbon footprint (greenhouse gas emission, GHGE) per 100g of product, together with high nutrient density scores per 100 units of energy if compared to other local staple foods such as maize meal and bread.

This study showed that different foods make unique contributions to the diet and have varying levels of greenhouse gas emission depending on production practices. Even though changes are needed to ensure a sustainable food system, these changes need to consider both the climate and also focus on maximizing the use of natural resources for the creation of healthy balanced diets. Furthermore, the actions that occur from farm gate to fork and thereafter also need to be taken into consideration and used as a point of departure to decrease the effect of food production on the environment.

In order to address and overcome issues pertaining to the environment, a wider societal, inter-sectoral and population-based public health approach is required. The problem that was created by everyone, needs input from everyone to be solved. If small changes are made by all individuals, a multiplier effect can be created, so that small behavioural changes produce large consequences for the environment. What is of greater concern is that this multiplier effect also works in vice versa. As there is only one planet to live on, taking care of it and ensuring sustainable futures for all is of the utmost importance.

It is evident, that the sustainability argument, which has mainly focused on the give and take between animal and grain products for the last few years, is an overly simplistic view of nutrition. Sustainable production of all agricultural products will have to be the way of the future. A healthy, balanced diet builds on the foundation of the right amounts of nutrient-dense foods from a variety of food groups, including lean meat, whole grains, vegetables, fruit and dairy products of high nutrient and sanitary quality.

This study showed that potatoes have an important role to play in many sectors varying from a food security crop all the way to a water-use-efficient crop. Potatoes are the staple food in South Africa that has the highest ND score associated with the lowest GHGE score. Potato crops use the least amount of water to produce not only the highest kilojoule output but also have the highest ND score per litre of water used.

Attention should be paid to the different agricultural practices used in the different regions to ensure that optimal input use efficiency is achieved. Overall potatoes proved to be an ND crop that uses fewer resources in comparison to other commonly consumed staple crops.

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Chapter 3: Protein quality of South African potatoes to inform dietary choices

"Nothing has such power to broaden the mind as the ability to investigate systematically and truly all that comes under thy observation in life." - Marcus Aurelius

Abstract

Determining amino acid content by summation is a more accurate description of total protein content of a product than using the Jones factor of 6.25. Protein content was determined using both the nitrogen to protein conversion factor as well as by summation of amino acids for four of the potato tubers (*Solanum tuberosum L.*) most commonly consumed in South Africa. Protein content for the tubers varied between 1.65g/100g and 2.14g/100g when using protein conversion and 1.64g/100g and 2.14g/100g when using the sum of amino acids with significant differences found between the amino acid content of the different tubers. Protein quality was evaluated using various methods. Even though the protein content of the tubers is low, it is of a high quality and can contribute to overall dietary protein consumption.

3.1 Introduction

The metabolic effect of specific individual dietary amino acids is important, demanding accurate information about the amino acid profile of foods. According to the Food and Agricultural Organisation (FAO) when evaluating dietary protein "*dietary amino acids should be treated as individual nutrients and wherever possible data for digestible or bioavailable amino acids should be given in food tables on an individual amino acid basis"* (FAO, 2011).

Protein is considered an important macronutrient in the diet as it provides both essential amino acids and is a source of energy. There has been much discussion regarding protein and amino acid requirements for both adults and children over the past years (Ghosh, et al., 2012). Internationally, the 2007 Food and Agriculture Organization/World Health Organization (FAO/WHO) report entitled: 'Protein and amino acid requirements in human nutrition', concluded that protein quality is of greater importance than actual quantity, emphasising the presence of individual amino acids in a food, instead of simply focussing on total protein (WHO, 2007). Determining the amounts of dietary essential amino acids, digestibility of protein and bioavailability of amino acids, facilitates the quantification of quality parameters of protein source foods (Gilani, et al., 2005).

Protein quality has been defined as the ability of a protein to achieve metabolic actions by providing specific patterns of amino acids and it is as important as protein content (Pretorius, et al., 2019;

MIllward, et al., 2008). The FAO report suggested that on average the recommendations for essential amino acids, particularly for lysine, should be doubled, and the recommended requirement for adults should be increased from 12 mg/kg body mass to 30 mg/kg (WHO, 2007). Data on the amino acid composition of foods is thus essential to improve global protein intake and health. The subject of the contribution of high quality foods to the diet is questioned at length in the recently released EAT-Lancet report. In this report it is estimated that there are 820 million people suffering from low quality diets which leads to a deterioration in human health. The report further promotes dietary changes to include foods that provide nutrients of high quality that can significantly decrease the number of individuals consuming low quality diets (EAT-Lancet , 2019).

Alternative sources of protein can make a significant contribution to protein intake of vulnerable individuals especially in countries where high quality proteins from animal source foods is scarce. Protein play a major structural role in the human body and are essential building blocks for muscles, encouraging tissue repair and development. Protein must be consumed in adequate amounts to achieve optimum nutritional status. It has been noted that protein malnutrition is a causative factor of 49% of more than 10 million annual deaths of children under five (Wang, et al., 2017). It is estimated that almost one third of children in developing countries are stunted, caused by long term insufficient intake of protein and energy. This emphasises the desperate need for alternative sources of high quality protein (Global Nutrition Report, 2018).

To meet the growing need for alternative sources of high quality protein, research on various supplementary crops is encouraged to determine the true and total nutritional value of food protein. Plant agriculture contributes significantly to social, economic and environmental outcomes at various levels throughout the agricultural sector. These crops provide livelihoods to farmers and contribute to nutrition outcomes. Globally the agriculture sector is facing increased pressure to produce enough food to feed the growing population, together with challenges of sustainability and water use efficiency. Together with sustainable inputs, high quality outputs are also required. Consequently, the production and consumption focus has shifted from energy dense diets to nutrient dense diets which will sustainably feed 10 billion people by 2050 in accord with the requirements needed for health outcomes (EAT-Lancet , 2019).

The South African Food-Based Dietary Guidelines (FBDG) encourage consumers to plan their meals around starchy foods and state that these foods should form the basis of most meals. The carbohydrates in starchy foods contribute significantly to the energy intake in the diet but can also be a source of other macronutrients and micronutrients that can contribute to human and dietary health. Potatoes are the most important non-cereal food crop with global production figure reaching 330 million tons (FAO, 2018). These tubers are consumed worldwide and regarded as a staple food in many countries, including South Africa. The versatility of this commodity has led to an expansion in the demand for potato products which has inevitably led to an increased contribution to dietary diversity through the production and consumption of various potato products (King & Slavin, 2013). In South Africa, potato consumption has increased by 26.8% associated with a 14.6% population growth showing that the total demand for potatoes increased by more than population growth i.e. increased per capita consumption (BFAP, 2019). This increase in consumption clearly shows what an important role potatoes play in the national diet. Due to some of the preparation methods, potatoes are often maligned in nutrition domains as being unhealthy and accused of contributing to the obesity epidemic. However, this is not a true reflection of the commodity, as a potato in its original form, cooked without the addition of fats and oils can form part of a balanced diet (Bártová, et al., 2015). Furthermore, it was recently reported that the biological value of potato protein is high (Camire, et al., 2009). Therefore, potatoes were chosen as the point of departure to investigate alternative sources of protein.

3.2 Objective

The purpose of the study was to determine the protein content and the amino acid profile of four different potato cultivars commonly consumed in South Africa. The protein as derived from the nitrogen content of the samples and multiplied with the Jones factor was compared to the sum of total amino acids. In addition, the protein quality scores were calculated.

3.3 Materials and methods

3.3.1 Sampling

Duplicate nutrient analyses were done on a composite sample of four potato cultivars obtained from various production regions across South Africa. Four cultivars that contribute to the largest market share (as shown in brackets) in South Africa were chosen for this study. Sampling was conducted during October – December 2018. Mondial (55%) and Sifra (23%) were sourced from three different production regions in South Africa i.e. Free State, Limpopo and Sandveld. The other cultivars Valor (6%) and BP1 (2%), were sourced from Limpopo as this was the region that was harvesting at the time of the study. All tubers were cultivated according to the common agricultural practices of each specific region under irrigation. Once harvested, 3kg tubers of each cultivar were packed in brown paper bags and transported to the laboratory. Upon arrival at the laboratory the tubers were stored in a cool dark room for six days to mimic market conditions. Prior to analyses, tubers were washed with water to remove all excess dirt and allowed to air-dry. Three whole tubers were randomly selected from each cultivar sample and analysed as a composite sample.

3.3.1.1 Determination of protein

Total nitrogen was determined using the Kjeldahl method. The nitrogen content was then used to calculate crude protein using the Jones conversion factor of 6.25. In 1981 a study to determine the nitrogen to protein conversion factor for potatoes was conducted using 34 different cultivars, which gave a factor of 6.24 which is similar to the empirical factor mostly used for foodstuffs. It was therefore decided that there is no reason to implement a potato specific conversion factor (Greenfield & Southgate, 2003; Van Gelder, 1981).

3.3.1.2 Determination of amino acids

The amino acid profile was determined by the ARC Irene Analytical Laboratory using high-performance liquid chromatography (HPLC) with florescence detection. The determination was carried out during three separate hydrolyses. The first hydrolysis analysed arginine, hydroxyproline, serine, aspartic acid, glutamic acid, threonine, glycine, alanine, tyrosine, proline, methionine, valine, phenylalanine, isoleucine, leucine, histidine and lysine. The ground freeze dried potato was weighed and hydrolysed with 6 N hydrochloric acid. An internal standard was added to the hydrolysate and filtered. A portion of the hydrolysate was dried under nitrogen-flow. The hydrolysate was derivatized with 9-fluorenylmethy chloroformate (FMOC-Cl) reagent and the amino acid content was determined by HPLC with an eluent of a tertiary gradient of pH, methanol and acetonitrile (Einarsson, et al., 1983).

The second hydrolysis determined cysteine and followed an identical approach as described above with the exception that prior to hydrolysis, cysteine was oxidised to cystic acid with a peroxide formic acid solution (Gehrke, et al., 1985). The third hydrolysis determined tryptophan. Ground freeze dried potato was hydrolysed enzymatically using protease. The hydrolysis was filtered through 0.45µg filter and tryptophan was determined by means of HPLC equipped with an AMinoTAg column and florescence detection (De Vries, et al., 1980).

3.3.2 Evaluation of the protein quality of foods for human consumption

In addition to the concentration of amino acids in foods, it is important to consider the digestibility of essential and non-essential amino acids in foods. Protein quality is typically measured using biological assays or chemical analysis as discussed below.

3.3.3 Analyses

Table 3-1 shows the summary of adult essential amino acid requirements which will be used for further comparison, discussion and calculation in this article. The values presented in Table 3-1 are the best currently available estimates for adult essential amino acid requirements (FAO/WHO/UNU, 2007).

Table 3-1: Summary of the adult essential amino acid requirements (FAO/WHO/UNU, 2007)

Amino Acid[a]	mg/kg body weight/day	mg/g maintenance protein
Histidine	10	15
Isoleucine	20	30
Leucine	39	59
Lysine	30	45
Sulphur Amino Acids	15	22
Methionine	*10*	*16*
Cysteine	*4*	*6*
Aromatic Amino Acids (Phenylalanine and Tyrosine)	25	38
Threonine	15	23
Tryptophan	4	6
Valine	26	39
Total essential amino acids	**184**	**277**

[a]Mean protein requirement of 0.66 g protein/kg per day

3.3.3.1 *Chemical score of essential amino acids*

Once the quantity of amino acids in the different cultivars was determined, the chemical score (CS) of the essential amino acids (CSEAA) or CS was calculated in relation to the amino acid pattern of the reference requirements (Table 3-1) proposed by the FAO (FAO/WHO/UNU, 2007; FAO, 2013), using the following equation (Eq 1) as first described by Mitchell and Block (1946).

$$\mathbf{CSEAA} = \left[\frac{(\mathbf{gEAA\ in\ test\ protein})}{(\mathbf{gEAA\ in\ reference\ protein})}\right] \qquad \text{(Eq 1)}$$

3.3.3.2 *Essential amino acid index*

The essential amino acid index (EAAI) measures the presence of amino acids that the human body cannot synthesise and gives a stronger indication of potential nutritive value. The essential amino acids index (IEAA) was calculated using the following equation (Eq 2) described by various researchers (Oser, 1959; Huang, et al., 2018; Rolinec, et al., 2018; Abdualrahman, et al., 2019).

$$\mathbf{EAAI} = \mathbf{100} \times \sqrt[n]{\frac{\mathbf{a}}{\mathbf{ap}} \times \frac{\mathbf{b}}{\mathbf{bp}} \times \frac{\mathbf{c}}{\mathbf{cp}} \times \ldots\ldots\ldots \frac{\mathbf{i}}{\mathbf{ip}}} \qquad \text{(Eq 2)}$$

where a, b, c, . . ., j = content of histidine, isoleucine, leucine, lysine, methionine, phenylalanine, tyrosine, threonine and valine in each sample; ap, bp, cp, . . ., ip = content of histidine, isoleucine,

leucine, lysine, methionine, phenylalanine, tyrosine, threonine and valine in the reference protein (FAO, 2013); n = number of amino acids used (counting pairs such as methionine and cystine as one).

3.3.3.3 Protein digestibility corrected amino acid score (PDCAAS)

Protein digestibility-corrected amino acid score (PDCAAS) is a method of evaluating the quality of a protein based on both the amino acid requirements of humans and their ability to digest the protein. The protein digestibility can be determined analytically, or can be approximated by using existing tables of the protein digestibility of foods. PDCAAS was calculated using the equation proposed by the FAO technical working group on protein quality and human requirements (Eq 4) (FAO/WHO, 1991; FAO/WHO/UNU, 2007). PDCAAS values > 1 were truncated to 1 (FAO, 2013).

$$\mathbf{PDCAAS} = \left[\frac{(\mathbf{g\ of\ limiting\ amino\ acid\ in\ test\ protein})}{(\mathbf{g\ of\ same\ amino\ acid\ in\ reference\ protein})}\right] \boldsymbol{x\ digestibility} \qquad \text{(Eq 4)}$$

3.3.3.4 Digestible indispensable amino acid score (DIAAS)

The FAO developed the digestible indispensable amino acid score (DIAAS) in 2013 as the new recommended method to determine protein value (FAO, 2013; FAO, 2014). This method takes into account both the individual amino acid concentration and its digestibility at the end of the small intestine, determined best with human models and if not, with pig or rat models, respectively (Rutherfurd, et al., 2015). It is calculated by dividing mg of digestible dietary indispensable amino acid in 1 g of the dietary protein by mg of the same dietary indispensable amino acid in 1 g of the reference protein (Eq 5) (FAO, 2013). For the calculation of DIAAS, the 2013 FAO Report recommends using human true ileal amino acid digestibility coefficients; pig true ileal amino acid digestibility coefficients; followed by rat true ileal amino acid digestibility coefficients, in that order of preference (FAO, 2013). An ileal digestibility value of 90 was used for the calculation (Branco-Pardal, et al., 1995). DIAAS values were not truncated.

$$\mathbf{DIAAS} = \left[\frac{(\mathbf{mg\ of\ digestable\ dietary\ indispensable\ amino\ acid\ in\ 1\ g\ test\ protein})}{(\mathbf{mg\ of\ the\ same\ dietary\ indispensable\ amino\ acid\ in\ 1\ g\ reference\ protein})}\right] \boldsymbol{x}\ \mathbf{100} \qquad \text{(Eq 5)}$$

3.3.4 Statistics

Data received from the laboratory was arranged in tabular format and statistically analysed using the GenStat for Windows (2008) statistical computer programme (Payne, et al., 2012). A one-way analysis of variance (ANOVA) test was applied with Fisher's protected *t*-test least significant difference at the 5% level of significance among cultivar means.

3.3.5 Results and discussion

This study measured and compared the amino acid profile of four different potato cultivars. These four cultivars form 86% of the South African potato market and are subsequently the most commonly consumed tubers. In Table 3-2 the protein and amino acid content of these four different tubers are reported.

As shown in Table 3-2, protein values using Nitrogen conversion did not differ significantly ($p=0.055$) between the various cultivars, ranging from the lowest value for Valor (1.65g/100g) to the highest value for BP1 (2.14g/100g). These values are similar to those found in the United States Department of Agriculture Food Composition Tables for the protein content of potatoes (2.03g/100g) (USDA, 2019), as well as traditional tubers as cultivated in the Canary Islands (1.94g/100g) (Galdon, et al., 2010).

The protein content of foodstuffs is determined by using a nitrogen to protein conversion factor. In the case of potatoes, the standard Jones factor of 6.25 is used. Critical reviews of the accuracy of the Jones factor for protein determination have delivered varying results depending on the food analysed. Some researchers state that the Jones factor is merely nitrogen expressed using a different unit and does not provide accurate results for true protein content (Mariotti, et al., 2008). A study of red meat found an underestimation of protein content when the Jones factor of 6.25 was used in the determination (Hall & Schönfeldt, 2013). In this study it was found that the Jones factor of 6.25 delivered accurate results when determining the protein content of potatoes. Variance between the calculated protein content and the sum of amino acids differed between 0% and 1% allowing the researchers to accept that the nitrogen to protein conversion factor of 6.25 can be used.

It is known that the nutritional and more specifically the amino acid contents of potatoes do vary and that the three greatest influencers, in order of effect are: cultivar (34.3%), nitrogen fertilisation (17.9%) and the conditions that occur during the growth phase (2.1%) i.e. year and site interactions (Bártová, et al., 2015; Grubben, et al., 2019). These findings were borne out when comparing the results from a previous study on the nutritional content of South African potatoes conducted in 2013 where tubers were planted under dry land conditions and had an overall lower protein content than tubers planted under irrigation as seen in the current study. Tubers from the 2013 study found overall lower protein values; Mondial; 1.45g/100g, Sifra; 1.00g/100g, Valor 1.35g/100g and BP1 1.96g/100g (van Niekerk, et al., 2016).

In the current study, of the nine essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine), five amino acid values differed significantly between the four cultivars (Table 3-2). The values for methionine and tryptophan were too similar and therefore statistical analysis could not be conducted on them. Amino acid values for histidine and lysine did not differ significantly between the different cultivars.

There are numerous methods to assess the nutritional value of proteins. Oser's method (one of the earlier methods) was used to rate the quality of protein based on the contribution of all the essential amino acids (Rao, et al., 1959). The essential amino acid index (EAAI) ranges from 1.367 for Mondial to 1.518 for BP1. All four tubers had an EAAI value above 0.90 and can therefore be classified as a good quality protein according to Oser's method.

Table 3-2: Amino acid content (mg) of four different potato cultivars

Analysis	**P-value**	**Mondial**	**Sifra**	**Valor**	**BP1**
Protein (N x 6,25) (g/100g)	p=0.055	1.770	1.940	1.650	2.140
Sum of amino acids		1.750	1.930	1.640	2.140
Essential amino acids (EAA)		0.675	0.740	0.675	0.860
Arginine	p≤0,05	0.135^{a}	0.135^{a}	0.105^{b}	0.12^{ab}
Histidine	p=0.603	0.055	0.050	0.040	0.040
Isoleucine	p≤0,05	0.05^{c}	0.06^{b}	0.065^{b}	0.08^{a}
Leucine	p≤0,05	0.075^{c}	0.095^{b}	0.09^{bc}	0.115^{a}
Lysine	p=0.052	0.115	0.120	0.110	0.145
Methionine	*	0.030	0.030	0.030	0.040
Phenylalanine	p≤0,05	0.06^{b}	0.065^{b}	0.07^{b}	0.095^{a}
Threonine	p≤0,05	0.055^{c}	0.07^{b}	0.06^{c}	0.08^{a}
Tryptophan	*	0.02	0.02	0.02	0.03
Valine	p≤0,05	0.080^{b}	0.095^{b}	0.085^{b}	0.115^{a}
Non-essential amino acids (NEAA)		1.075	1.185	1.965	1.275
Alanine	p≤0,05	0.055^{c}	0.08^{a}	0.06^{c}	0.07^{b}
Aspartic acid	p≤0,05	0.345^{b}	0.315^{b}	0.355^{b}	0.475^{a}
Cystine	p=0.258	0.025	0.025	0.020	0.040
Glutamic acid	p≤0,05	0.42^{b}	0.495^{a}	0.27^{c}	0.375^{b}
Glycine	*	0.05	0.05	0.05	0.06
Proline	p=0.4	0.055	0.075	0.08	0.08
Serine	p≤0,05	0.055^{c}	0.07^{b}	0.06^{c}	0.08^{a}
Tyrosine	p≤0,05	0.06^{b}	0.065^{b}	0.06^{b}	0.085^{a}
Methionine + Cystine	p=0.08	0.055	0.055	0.050	0.080
Phenylalanine +Tyrosine	p≤0,05	0.12^{b}	0.13^{b}	0.13^{b}	0.18^{a}
EAA/NEEA Ratio		0.628	0.624	0.699	0.675
PDCAAS		1	1	1	1
DIAAS		101	99	108	114
Essential amino acid index (EAAI)		1.37	1.37	1.49	1.52
Essential amino acid index %		137	137	149	152

*Values for these amino acids did not show variance and therefore no statistical analysis was possible
[#]Means with different superscripts in a row differ significantly

In Table 3-3 the chemical score of essential amino acids (CSEAA) with the lowest value indicates the first limiting amino acid. For potatoes leucine was found to be the first limiting amino acid as it had a score of less than 1. These results are in agreement with the results of a study conducted in Denmark where leucine was also found to be the first limiting amino acid in potatoes (Jorgens & Lauridsen, 2004). Leucine is one of the three branched chain amino acids (BCAA) which play an essential role in protein synthesis and is critical in metabolic proses (Layman, 2003). Consuming plant foods, such as beans, soya, lentils or split peas, which are high in leucine, together with potatoes, can contribute to the intake of complete protein (Pretorius, et al., 2019).

Table 3-3: Chemical score of essential amino acids (CSEAA)

Analysis	**Mondial**	**Sifra**	**Valor**	**BP1**
Histidine	2.10	1.73	1.63	1.25
Isoleucine	0.95	1.04	1.32	1.25
Leucine	**0.73**	**0.84**	**0.93**	**0.91**
Lysine	1.46	1.39	1.49	1.51
Sulphur Amino Acids Methionine and Cystine	1.43	1.30	1.39	1.70
Aromatic Amino Acids Phenylalanine and Tyrosine	1.80	1.78	2.09	2.22
Threonine	1.37	1.58	1.59	1.63
Tryptophan	1.90	1.73	2.03	2.34
Valine	1.17	1.27	1.33	1.38

The protein digestibility– corrected amino acid score (PDCAAS), was adopted as the preferred method for measurement of the protein quality in human nutrition in 1993. However, the truncation of PDCAAS to 1.0 means that important information on highly nutritious proteins is discarded. This truncation is done to 1 if the protein value exceeds 1 using the PDCAAS calculation (Millward, 2012; FAO, 2013; Joye, 2019). This is the case in the current study where all the PDCAAS values were truncated to 1 and, therefore no conclusions could be drawn. A more recent protein quality score, as proposed by the FAO in 2013, is the digestible indispensable amino acid score (DIAAS), that compares the content of all digestible essential amino acids in a protein to the level of these digestible amino acids in a reference protein. The adoption of this new method to measure the quality and digestibility (bioavailability) of dietary proteins reflects the advances made in analytical methods in order to provide more accurate data (British Nutrition Foundation, 2013). The DIAAS values for the cultivars ranged from 99 for Sifra and 114 for BP1. In comparison soya, which is commonly regarded as a high quality protein plant based food, has a DIAAS value of 90 (Pretorius, et al., 2019).

In Table 3-4 the protein, sum of amino acids, PDCAAS, DIAAS, EAAI and ratio of essential to non-essential amino acids of potatoes is compared to high protein plant based foods. The values for potatoes are the averaged values of the four cultivars analysed in this study. In this comparison potatoes are the food with the lowest protein content. The PDCAAS values for potatoes, beans, lentils and soy were truncated to one. Chickpeas and split peas had PDCAAS values of 0.96 and 0.92 respectively. DIAAS values ranged between 81 for beans and 132 for lentils. Potatoes had a DIAAS value of 106 which is an average score compared to the other foods in Table 3-4. Potatoes had the lowest score for EAAI at 1.44 with beans scoring highest at 1.98. All the foods had an EEAI score above 0.90, which indicates that they are all classified as a good quality protein. Potatoes, chickpeas, lentils, split peas and soy had similar EAA/NEEA ratios, and beans had the highest score of 0.84.

Table 3-4: Protein quality measures for potatoes and high protein plant based foods

	Potatoes	Dry Haricot Beans*	Tinned Chick-peas*	Dry Lentils*	Dry Split peas*	Dry Soy*
Protein (N x 6.25) (g/100g)	1.88	20.87	19.87	24.83	21.77	36.45
Sum of Amino Acids	1.87	19.93	18.69	22.56	21.06	35.78
PDCAAS	1	1	0.96	1	0.92	0.6
DIAAS	106	81	94	132	106	90
Essential amino acids index EAAI	1.44	1.98	1.66	1.65	1.66	1.53
EAA/NEAA ratio	0.66	0.84	0.61	0.62	0.66	0.64

* (Pretorius, et al., 2019)

3.4 Conclusions and recommendations

On average raw potatoes contained 1.6 – 2.1 g/100g protein. In general crude protein content as calculated using the Jones factor of 6.25 corresponded well with the sum of amino acids. When using the essential amino acid index and DIAAS all four potato cultivars that were analysed can be classified as containing protein of good quality. Leucine was found to be the first limiting amino acid in potatoes, which is an amino acid that is commonly limited in plant based products. If PDCAAS was used to describe the protein quality, all values were truncated to 1, which may mean that valuable information was lost due to truncation. DIAAS values ranged from 99 for Sifra to 114 for BP1. This is numerically higher than the DIAAS values for soya of 90.

Even though potatoes are not typically considered as a source of protein, due to the its low protein content, the unique amino acid composition allows potatoes to be regarded as a plant based food that contains high quality protein. This study provides evidence that potatoes can contribute to dietary protein quality intake compared to other plant based foods as compared in this study. Further investigations to identify tubers that contain more protein of good quality are recommended. The development and cultivation of tubers with a higher protein content of good quality should also be studied.

3.5 References

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Chapter 4: Evaluating the effect of external conditions on the quality attributes of potatoes

"What I say is that, if a fellow really likes potatoes, he must be a pretty decent sort of fellow."

– A.A. Milne

Abstract

The rapidly growing global population emphasises the need for high yielding, sustainable, yet nutritious food crops, that produce consistent yields under varying agricultural conditions. There are various critical research hypotheses that propose solutions for this scenario with some of the main focus areas being crop management and precision farming practices. Even though these practices are mainly focused on improving economic output, the further downstream effect is increased food security. The objective of this study was to determine the effect of genome - environment interactions to identify possible regions were specific cultivars are better suited than others.

Internal quality and external variable data gathering for this study stretched over three years (2016-2018) throughout South Africa on ten different plots. The Additive Main Effects and Multiplicative Interaction (AMMI) model was used to determine the reaction of cultivars/lines in each environment and display the stability of these genotypes in the different environments.

The AMMI model showed that certain cultivars are more stable in varying geographical areas i.e. they delivered consistent results irrespective of the external factors that they were exposed to. It was found that genomes and environments that are stable are less likely to be influenced by external variables.

4.1 Introduction

The changing agricultural landscape, together with shifting consumption patterns associated with an increase in diseases of lifestyle epidemics, have led to the need for food production systems that, not only deliver sufficient energy, but also provide nutrients to sustain human health while taking sustainable outcomes into consideration. This is all in an attempt to sustain the rapidly growing global population emphasising high yielding, sustainable, yet nutritious food crops that produce consistent yields under varying agricultural conditions to feed 10 billion people by 2050 (WHO, 2018). Various critical research hypotheses have been proposed for this scenario. Some of the main themes which are being investigated are to improve crop management and precision farming practices (Tein, 2009). However, these fairly ambitious plans are influenced by temporal variation, a lack of region specific focus and a lack of environmental auditing knowledge. Many countries are implementing general typology plans as developed internationally, especially in lower income areas, without considering country and even region specific variables. Even though these generic plans do address and in some instances solve the negative issues, region-specific scientific data is required to further improve and sustain these solutions (McBratney, et al., 2005).

Precision agriculture and region specific agriculture are classified as modern farming practices that aim at improving production efficiency and rely on the mantra "what gets measured, gets managed". Precision agriculture entails observing, measuring and subsequently responding to inter- and intra-field variations observed in crops. Even though these practices are mainly focused on improving economic output of farming practices, the additional downstream effect is increased food security (Walter, et al., 2017). Precision agriculture is also linked s to achieving Goal 12 - "responsible production and consumption" - of the Sustainable Development Goals (SDGs) as adopted by the United Nations on 25 September 2015. These 17 goals aim to end poverty, protect the planet and ensure prosperity for all by 2030 (UNDP, 2019).

Responsible production entails input use efficiency in agriculture by means of region specific agriculture to promote crops and cultivars that are ideally suited to specific environments and to achieve optimum yields and nutritional outputs (UN, 2018) with an added benefit of consumer acceptance. Potato crop yields per unit area have shown noteworthy increases over the last 20 years in South Africa. In 1990, 130 million 10kg bags were produced on 63 000 ha, whereas in 2018, this figure rose to 240 million 10kg bags, which were produced on 52 000 ha (Potatoes South Africa, 2019). Inappropriate crop management practices are, however, still common, leading to a decrease in possible yields, as well as having detrimental effects on the environment (Steyn, 2016). With the threat of a rapidly growing population, optimisation of input use efficiency and yields is essential.

In this study the effect that external variables have on the internal quality attributes of South African potatoes is investigated. It is hypothesised that specific cultivars may be more ideally suited to specific growing conditions and, therefore, also specific geographical regions with regard to increased yield and quality.

4.2 Objective

The objective of this study was to determine the effect of cultivar-environment interactions to identify possible regions were specific cultivars are better suited to grow than others.

4.3 Methodology

Data gathering for this study took place over a three-year period (2016-2018) across South Africa from ten different plots (Table 4-1). Figure 4-1 is a map of South Africa showing the different production regions from which potatoes were sourced for this study. All the tubers were planted as part of Potatoes South Africa's workgroup project under the standardised agronomical practices (agronomic management) of the specific areas using randomized block designs (RBD).

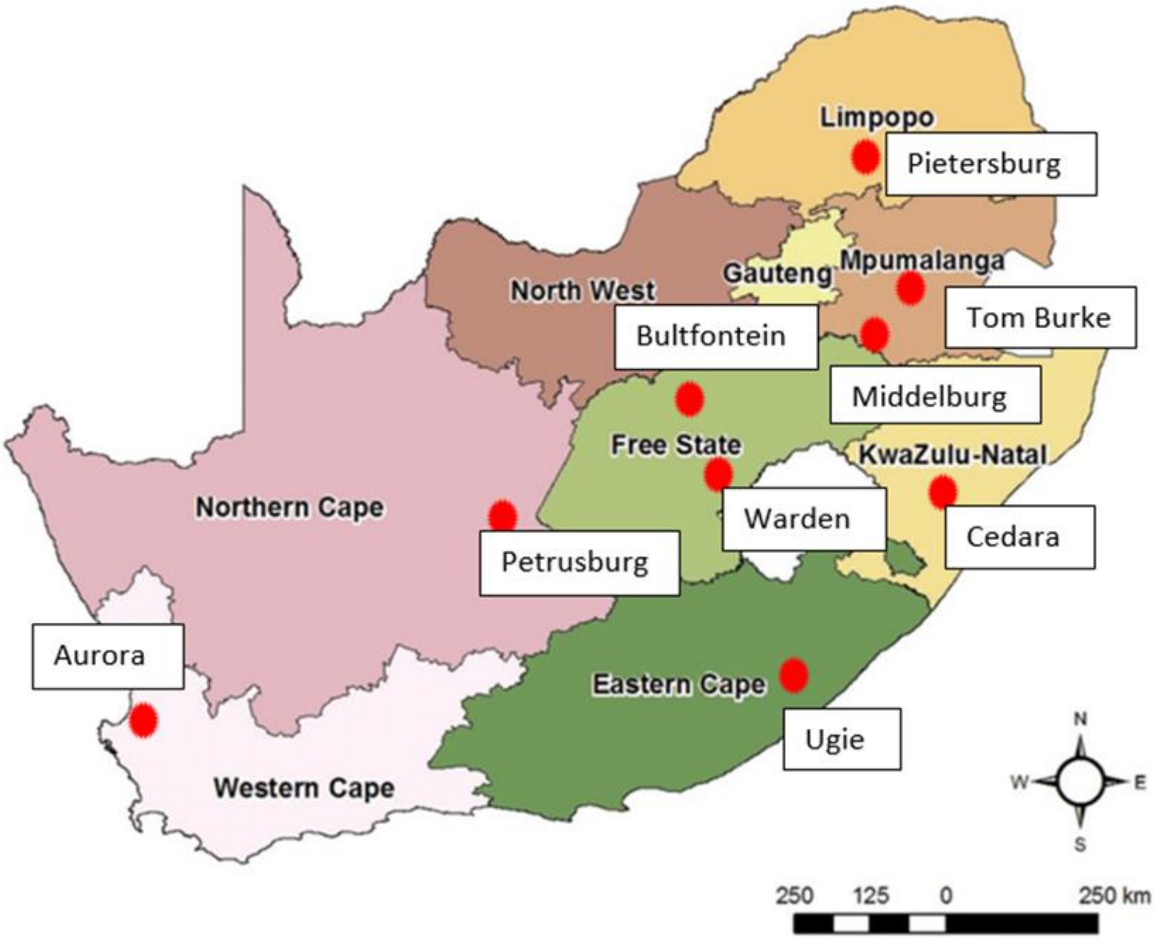

Figure 4-1: Map of South African showing all the different production regions from which potatoes were sourced for this study

4.3.1 Potato sampling procedures

At harvest random samples of tubers were selected and packed by the potato trial leader, into 10kg brown bags and transported to the laboratory in Pretoria within 12 hours after being harvested. Table 4-1 is a summary of the harvest areas and agricultural practices used for the tubers for this study. Tubers were kept in the bags at 21 ˚C for six days postharvest, prior to analysis to mimic market practices. On the day of analyses, each bag per cultivar was emptied into a container, mixed and tubers were randomly selected for the laboratory tests. Selected tubers were thoroughly washed with distilled water and allowed to dry on paper towels.

Table 4-1: Location, date of harvest and agricultural practices used for tubers sourced for use in the study

Region	Harvest date	Precipitation
Bultfontein	17-Aug-16	Irrigation
Pietersburg	08-Dec-16	Irrigation
Middelburg	01-Feb-17	Irrigation
Aurora	15-Mar-17	Irrigation
Warden	13-May-17	Dry land
Ugie	23-May-17	Irrigation
Tom Burke	17-Oct-17	Irrigation
Pietersburg	08-Dec-17	Irrigation
Petrusburg	25-Jan-18	Irrigation
Cedara	05-Feb-18	Irrigation

4.3.2 Internal quality attributes

4.3.2.1 Dry matter analysis

Three fresh, "as is", tubers from each cultivar from each production area were sent in a brown paper bag for dry matter analysis. These tubers were selected at random from the 10kg bags as received from the farm. Dry matter was gravimetrically determined according to the AOAC (Association of Official Agricultural Chemists) 934.01 method at a SANAS (South African National Accreditation System) accredited laboratory. Analyses were done in duplicate on the flesh and skin of each tuber.

Dry matter content is seen as more reliable method than specific determination as it is a validated analytical method of evaluation. Dry matter is measured by drying a known wet weigh of finely grated tuber, placing it in a drying oven to extract all the moisture from the flesh and then weighing it again to determine the total dry matter content (AOAC, 2000).

4.3.2.2 Specific gravity analysis

Five randomly selected tubers from each cultivar from each production area were individually analysed for specific gravity. Specific gravity was determined by weighing (washed and dried) tubers (flesh and skin) individually. This was followed by an underwater weighing where the tubers were individually placed in a net and submerged in water and weighed. Specific gravity is then calculated with the following equation (Eq. 1) (DAFF, 2013):

$$Specific\ gravity = \frac{Weight\ in\ air}{(Weight\ in\ air - Weight\ under\ water)} \qquad \text{(Eq. 1)}$$

4.3.2.3 Chip colour

Chip colour analyses were done at the Roodeplaat Institute of the Agricultural Research Council, South Africa. Chipping colour analyses were done using the Hunterlab method, as described by the United States Department of Agriculture (USDA, 1977). The test determines compliance with a specified fry colour. The South African potato industry standards for acceptable chip colour is set at 50>.

Chips were made by frying potato slices, 1.3 mm thick from the centre portion of the potato sliced longitudinally, in oil with a starting temperature of 185°C for 1 minute 40 seconds. A minimum of 40 slices were used for colour evaluation. Visual colour scoring was done on a scale of 1-10 with 1 denoting the lightest colour and 10 denoting the darkest colour with associated designations as shown in Table 4-2 (USDA, 1977; Ezekiel, et al., 2003).

Table 4-2: Hunterlab colour values corresponding to different chip colour scores (Ezekiel, et al., 2003)

Chip colour score	Mean	Range
1	81.0	80-82
2	77.3	75-79
3	69.3	67-74
4	62.0	61-66
5	55.7	54-60
6	51.7	50-53
7	48.3	45-49
8	40.1	40-44
9	37.7	36-39
10	30.0	25-35

4.3.3 External variables

4.3.3.1 Marketing index

To determine the performance of the cultivars in terms of yield and quality, the yield, size distribution and class were used to calculate a marketing index at the average market prices the day of harvest. The yield, multiplied by the prevailing price determined by the size distribution and rating, gives the marketing index (Eq.2) (Potatoes South Africa, 2019).

$$Marketing\ index = \frac{crop\ yield\ per\ hectare \times market\ price\ on\ day\ of\ harvest}{100} \qquad \text{(Eq.2)}$$

4.3.3.2 Weather data

Data used for rainfall and heat unit calculation was sourced from the Agricultural Research Council Agro-Meteorology Programme for weather stations. These weather stations are situated on more than 500 plots throughout South Africa and maintain an operational national agro-climate network database, as well as a climate databank (ARC, 2019). Rainfall data as received from the weather station was summed over the growing period.

Subsequently, heat units were calculated from the weather data using the set formula as describe in horticulture guidelines (Eq. 3). A threshold value of 5.00 was used for potatoes (Worthington & Hutchinson, 2005).

$$Heat\ unit = \frac{(Temperature\ \max + Temperature\ min)}{2} - (Threshold\ Temperature) \qquad \text{(Eq.3)}$$

4.3.3.3 Fertilizer

Fertilization practices and amount of fertilizer applied at the beginning, as well as throughout the planting cycle, were noted. Fertilizer application is area specific and data was obtained from each individual farmer on the amount of fertilizer that was applied during the growing period. Fertilizer is expressed as kg per hectare for nitrogen, phosphorus and potassium.

4.3.3.4 Plants and yield per hectare

Plants and yield per hectare were calculated using the following equations:

$$\frac{10\ 000\ m^2}{sample\ area\ m^2} = \text{Multiplying factor} \qquad \text{(Eq. 4)}$$

$$\frac{kg\ yield\ or\ plants\ from\ sample\ area}{1000} = \text{ton or plants per sample area} \qquad \text{(Eq.5)}$$

$$ton\ /\ plants\ per\ sample\ area\ (Eq. 5) \times multiplying\ factor (Eq. 4) = tons\ /\ plants\ per\ hectare \qquad \text{(Eq.6)}$$

4.3.3.5 Cultivar class, size and waste

Potato class and size were evaluated according to the guidelines supplied by the Department of Agriculture and Potatoes South Africa. Potatoes sizing is classified as shown in Table 4-3. Potatoes are scored in classes based on the absence of diseases and blemishes visible to the eye and the presence of quality factors as stipulated by specific end users (DAFF, 2019).

Table 4-3: Sizing guide for potatoes in South Africa (DAFF, 2019)

Sizing	Weight in g
Baby	5 – 50
Small	50 – 100
Medium	90 – 170
Large Medium	150 – 250
Large	250 +

4.3.4 Statistical analysis

All data for the internal and external evaluations were captured on a spreadsheet. A one-way random block design (RBD) analysis using Fisher's protected least significant differences (FPLSD) t-test at the 5% level of significance, was used to separate means among cultivars for dry matter and specific gravity (Payne, et al., 2012).

The cultivar-environment interaction was analysed using the AMMI model (Gauch, 2013). The AMMI-model is suitable for determining the reaction of cultivars/lines in an environment and displays the stability of these genotypes in different environments (Steyn, et al., 1993). This model is explained by sums of additive and multiplicative terms which result from the singular value decomposition (SVD) or principal component analysis (PCA) of the interaction matrix ($p<0.01$). The model had a two-way factorial design, with each treatment specified by a genotype and environment combination. If a cultivar or an environment has an Interaction Principal Component (IPC) score near zero it has a small interaction, thus is stable in response. A cultivar or environment which lays further from zero are more sensitive to interactions and thus show more variance (Smith & Smith, 1992).

In an attempt to elucidate the variance that is observed between cultivars and over regions, an AMMI model was constructed to investigate the cultivar-environment interaction for the internal characteristics (i.e. dry matter and specific gravity). For both of these characteristics, six different cultivars namely Markies, Valor, Lanorma, Sifra, Taisiya and Mondial were selected together with ten environments i.e. Tom Burke, Petrusburg, Warden, Middelburg, Cedara, Ceres, Aurora, Pietersburg 2016, Pietersburg 2017 and Ugie. Each interaction was tested three times.

The AMMI model was constructed using 20 variables: Fertilizer (Nitrogen, Phosphorus, Potassium), Internal characteristics (Dry matter, Specific gravity, Chip colour, Sizing (baby, small, medium, large-medium, large), Cultivar classes (1, 2, 3), Heat units, Plants per hectare, Rainfall, Yield in tons per hectare, Marketing index, and Waste.

4.4 Results and discussion

In Table 4-4, the specific gravity and dry matter means are compared for various cultivars over the regions in which the different cultivars were grown and analysed at the 5% significance level. Significant differences were found for specific gravity between different cultivars in six of the ten regions: Aurora (p=0.040), Cedara (p=0.044), Middelburg (p=0.023), Petrusburg (p=0.008), Pietersburg 16 (p<0.001) and Warden (p=0.002). Significant differences were found for dry matter values between different cultivars in four of the ten regions i.e. Aurora (p=0.048), Ceres (p=0.026), Middelburg (p=0.0.31) and Pietersburg 16 (p<0.001).

Fianna was the only cultivar that showed no significant difference between the various regions for specific gravity (1.064 – 1.071) and dry matter (17.52 – 20.31). All the other cultivars differed significantly over the various regions for specific gravity and dry matter. From this data it is evident that the environment plays a significant role in the specific gravity and dry matter values of different potato cultivars.

Specific gravity is one of the most common methods used in the potato industry to determine the cooking and chipping quality of tubers as specific gravity is a determining factor of textural properties and cooking quality (Potatoes South Africa, 2019).

As specific gravity measurements are simpler to obtain than dry matter values, this method is used more often as the chosen method of evaluation. Oregon State University developed a specific gravity and dry matter reference guide which indicates the relationship between specific gravity and dry matter. Specific gravity measures most commonly fall in ranges between 1.055 - 1.095 with correlating dry matter values of between 16.5%-24% (Oregon State University, 2010). In a study conducted in Pakistan the specific gravity of 32 different cultivars of potatoes was found to vary between 1.034 - 1.144 (Abbas, et al., 2011), which is a wider and higher range than the average values seen in European (1.045 - 1.085) potatoes (Anzaldua-Morales, et al., 1992). A more recent study in Japan showed specific gravity values ranging from 1.055 - 1.110. The minimum value of the range is higher than that seen in Europe and Pakistan together with a higher top range value (Sato, et al., 2017). In the current study specific gravity ranged between 1.040 - 1.080 and dry matter between 13.04 - 21.10. This can be explained by the different cultivars and agronomical methods that are used in different countries.

Starch, which is the main carbohydrate found in plants, is the major storage compound found in potatoes. Starch content is directly related to specific gravity or dry matter in tubers. According to the Oregon State University guidelines 60-80% of the dry matter is present as starch (Oregon State University, 2010). A study conducted in South Africa in 2016 found that 67-74% of dry matter is present as starch (van Niekerk, et al., 2016). Therefore, high-gravity or high-solids tubers are associated with high levels of starch.

There is a significant difference in the distribution of dry matter throughout the flesh and skin of the tuber. Peeling, slicing and handling can have an effect on the dry matter content of a tuber. With this all taken into account, dry matter is still the best way to evaluate the total quantity of solids in a tuber (Thybo, et al., 2004). The higher the dry matter content, the lower the water content, which will mean that such a potato, has a higher specific gravity. Potatoes with a higher dry matter and low moisture content are mealy, and ideal for baking. Potatoes with a low dry matter and high moisture content are waxy and ideal for boiling (South African Department of Environment and Primary Industries, 2000).

Table 4-4: Specific gravity and dry matter analysis of seven cultivars tubers over ten regions

Specific Gravity								
		Cultivar						
Area	**p-value**	**Sifra**	**Lanorma**	**Mondial**	**Markies**	**Fianna**	**Valor**	**Taisiya**
p-value	**p<0.05**	<0.001	<0.001	<0.001	<0.001	0.354	<0.001	<0.001
Aurora	0.040	1.061$^{a, ii, iii}$	1.063$^{a, ii, iii, iv}$	1.068$^{ab, ii, iii}$	1.071$^{b, iv, v}$	1.071^{b}		
Cedara	0.044	1.080$^{c, iv}$	1.074$^{bc, vi}$	1.069$^{ab, iii}$			1.073$^{abc, iii}$	1.064$^{a, iii}$
Ceres	0.411	1.062$^{ii, iii}$	1.061$^{ii, iii}$	1.059^{ii}	1.060$^{ii, iii}$	1.070		1.056^{ii}
Middelburg	0.023	1.050$^{ab, i}$	1.057$^{bc, ii}$	1.045$^{a, i}$	1.047$^{ab, i}$	1.064^{c}	1.049$^{ab, i}$	
Petrusburg	0.008	1.076$^{bc, iv}$	1.071$^{ab, v, vi}$	1.078$^{c, iv}$	1.065$^{a, iii, iv}$			1.066$^{a, iii}$
Pietersburg 16	<0.001	1.056$^{b, i, ii}$	1.065$^{c, iii, iv, v}$	1.045$^{a, i}$	1.076$^{d, v, vi}$		1.055$^{b, I, ii}$	
Pietersburg 17	0.072	1.066^{iii}	1.070$^{iv, v, vi}$	1.062$^{ii, iii}$			1.059^{ii}	
Tom Burke	0.057	1.076^{iv}		1.069^{iii}	1.080^{vi}		1.069^{iii}	
Ugie	0.053	1.051^{i}	1.047^{i}	1.040^{i}				1.047^{i}
Warden	0.002	1.058$^{i, ii, iii}$	1.060$^{ii, iii}$	1.042^{i}	1.056^{ii}		1.054^{i,ii}	1.055^{ii}
Dry Matter								
		Cultivar						
Area	**p-value**	**Sifra**	**Lanorma**	**Mondial**	**Markies**	**Fianna**	**Valor**	**Taisiya**
p-value	**p<0.05**	<0.001	0.007	0.001	0.286	0.230	<0.001	0.008
Aurora	0.048	14.28$^{a, i, ii}$	15.17$^{ab, i, ii}$	16.34$^{abc, iii}$	17.47$^{bc, i}$	17.52^{c}		
Cedara	0.113	16.57$^{iii, iv, v}$	14.81$^{i, ii}$	16.97$^{iii, iv}$			18.00^{ii}	15.57^{ii}
Ceres	0.026	16.37$^{ab, ii, iii, iv}$	16.58$^{ab, i, ii}$	15.32$^{a, ii, iii}$	18.05$^{bc, i, ii}$	19.59^{c}		17.06$^{ab, ii}$
Middelburg	0.031	16.85$^{ab, iii, iv, v}$	19.20$^{bc, iii}$	16.14$^{a, iii}$	18.12$^{abc, i, ii}$	20.31^{c}	17.23$^{ab, ii}$	
Petrusburg	0.357	18.25$^{iv, v}$	17.16$^{ii, iii}$	16.40^{iii}	19.62$^{i, ii}$			16.39^{ii}
Pietersburg 16	<0.001	14.01$^{b, i}$	16.16$^{c, i, ii}$	11.98$^{a, i}$	18.29$^{d, i, ii}$		14.32$^{b, i}$	
Pietersburg 17	0.812	14.84$^{i, ii, iii}$	14.54^{I}	14.40$^{i, ii, iii}$			15.37^{i}	
Tom Burke	0.199	18.56^{v}		19.30^{iv}	21.10^{ii}		18.09^{ii}	
Ugie	0.758	13.94^{i}	14.34^{i}	13.04$^{i, ii}$				13.81^{i}
Warden	0.080	17.35$^{iv, v}$	17.13$^{ii, iii}$	15.42$^{ii, iii}$	20.27^{i,ii}		18.23^{ii}	17.18^{ii}

Super script letters show significant differences over cultivars
Roman numerals show significant differences over regions

Table 4-5 is a summary of all the data as captured over three years, ten environments/regions and the tubers that had enough data entries for robust statistical analysis (Markies, Lanorma, Sifra, Valor and

Taisiya). This table shows the minimum, maximum and mean values of all the variables that were measured. In total 150 values were captured for each variable.

The initial data showed that there was no significant cultivar-environment interaction for the internal quality attribute of dry matter (p=0.093) and it will, therefore, not be discussed any further (Figure 4-3). Specific gravity had a cultivar-environment interaction at a 0.0000004 level of probability making it highly significant.

Table 4-5: Summary of data as used in AMMI Model for all cultivars and environments/regions

Identifier	Minimum	Mean	Maximum
SG	1.035	1.062	1.085
DM	11.22	16.66	22.35
Plants/ha	37037	42128	51680
Yield ton/ha	13.33	62.47	127.2
Marketing Index	54.30	100.4	146.9
Chip Colour	36.60	50.68	63.20
Nitrogen	239.6	286.9	363.0
Phosphorus	80	119.7	192.6
Potassium	67	217.2	496.9
Class 1	8.81	48.50	119.7
Class 2	0	13.27	65.51
Class 3	0	4.942	34.04
Large	0	18.54	75.35
Large-medium	1.93	15.83	45.29
Medium	0	19.30	62.67
Small	0	7.852	23.16
Baby	0	3.474	14.16
Waste	0	0.2084	4.410
Heat unit	1308	1868	2805
Rainfall	0	350.2	763.1

Interaction Principal Component (IPC) scores were calculated using data reported in Table 4-5. IPC1 scores are the scores that identified significant interaction scores. Lower IPC1 scores show a cultivar or environment that is more stable, while higher IPC1 scores show cultivars or environments that are more sensitive. Figure 4-2 shows the graph plotting the IPC1 scores against specific gravity. Table 4-6 shows the mean specific gravity and IPC1 scores using the AMMI model. These are the values that were transposed into the graph in Figure 4-2. Cultivars and environments plotted closer to the x-axis proved to be more stable than cultivars and environments that lay further away from this axis. The further the values are from the x-axis the more sensitive they are. Values close to the y-axis had average specific gravity scores. Values to the right of the y-axis had higher specific gravity values on average, while cultivars and environments on the left side of the y-axis had lower than average specific gravity scores. Cultivars and environments that are stable are less likely to be influenced by external variables. External variables are more likely to have an effect on the internal quality attributes i.e. specific gravity, of cultivars and environments that fall within the sensitive category.

Table 4-6: AMMI model for specific gravity showing ranked means and IPC1 scores

Cultivar		
	Mean (SG)	*IPC1 Score*
Lanorma	1.064	0.0197
Markies	1.064	0.1006
Sifra	1.063	-0.0437
Taisiya	1.060	0.0667
Valor	1.059	-0.0428
Mondial	1.057	-0.1005
Environment		
	Mean (SG)	*IPC1 Score*
Tom Burke	1.0674	0.0271
Petrusburg	1.0717	-0.0904
Cedara	1.0715	-0.0569
Pietersburg 2017	1.0650	0.0120
Aurora	1.0647	-0.0064
Pietersburg 2016	1.0608	0.1204
Ceres	1.0594	-0.0285
Warden	1.0541	0.0243
Middelburg	1.0491	-0.0176
Ugie	1.0466	0.0159

In Table 4-7 the AMMI score ranks are shown, together with the mean values for the following variables: plants per hectare, yield per hectare, marketing index, fertilizer, heat units and rainfall. Three separate environmental groups were identified from the AMMI ranks. The first group consists of Pietersburg 2016, Tom Burke, Warden, Ugie and Pietersburg 2017. In these five environments Markies was the cultivar that consistently performed the best i.e. obtained a rank of 1. Sifra was the most stable and scored the highest SG values when planted specifically in Aurora, Middelburg and Ceres. Mondial was the most stable with the highest SG values in Cedara and Petrusburg.

Table 4-7: AMMI Scores and variables for IPC1

	AMMI Rank						Variables Mean							
Environment	**Markies**	**Lanorma**	**Sifra**	**Valor**	**Mondial**	**Taisiya**	**Plants per ha**	**Yield**	**Marketing index**	**Nitrogen**	**Phosphorus**	**Potassium**	**Heat Unit**	**Rainfall**
Pietersburg 2016	**1**	6	2	3	4	5	41666	52,22	103	250	81	128	2192	286
Tom Burke	**1**	2	6	3	4	5	37037	59,03	104	301	142	106	2805	39
Warden	**1**	2	3	6	4	5	41666	45,15	98,8	280	80	95	2409	577
Ugie	**1**	2	3	6	4	5	44444	17,66	76,3	271	100	67	1345	445
Pietersburg 2017	**1**	2	3	6	4	5	41666	57,88	124	250	81	128	1642	306
Aurora	2	3	**1**	6	4	5	41666	97,11	97,6	313	193	497	2558	0
Middelburg	3	2	**1**	4	5	6	44444	68,08	103	306	108	314	1414	76
Ceres	3	2	**1**	4	5	6	51680	96,89	103	363	146	449	1463	24
Cedara	3	2	5	4	**1**	6	37037	63,22	105	240	110	146	1308	640
Petrusburg	3	5	4	2	**1**	6	37037	54,30	102	270	154	130	1642	306

From Figure 4-2, it can be seen that the following environments: Ugie, Warden, Pietersburg 2017, Tom Burke, Middelburg, Aurora and Ceres were the most stable environments and thus these areas produced cultivars that had consistent results for specific gravity. Petrusburg and Cedara were sensitive to external variables, as well as Pietersburg 2016, which was the most sensitive environment. It was observed that although the locality was the same for the two environments, Pietersburg 2016 and 2017, the heat units during 2016 were numerically higher which could be responsible for the sensitivity of the area in 2016. Tubers planted in these sensitive regions delivered inconsistent results for specific gravity. The most stable cultivar was Lanorma, followed by Valor and Sifra. These three cultivars were the most stable in all the environments delivering consistent values for specific gravity. Taisiya was a more sensitive cultivar. Markies was the most stable in Pietersburg 2016, Tom Burke, Warden, Ugie and Pietersburg 2017. However, when all the environments are considered, Mondial and Markies were the most sensitive cultivars. These cultivars did not have consistent specific gravity results.

It must be noted that the one region, Warden, which was planted under dry land conditions did not perform significantly differently to regions which made use of irrigation. This is in contrast to what was found in a study conducted in 2013 that found that tubers planted under dry land conditions differed significantly to tubers planted under irrigation. It was found that tubers planted under irrigation tend to elicit more cultivar specific characteristics, while tubers that were planted in dry land conditions tend to be similar in terms of textural properties (Booysen, et al., 2013). Furthermore, rainfall patterns are notoriously hard to analyse and difficult to use for obtaining significant statistical correlations. Average rainfall is a relative concept as the average rainfall may stay the same but other factors such as, higher temperatures: increased evapotranspiration rates and the lengths of dry spells all exert effects on the true water availability (South African Weather Services, 2019).

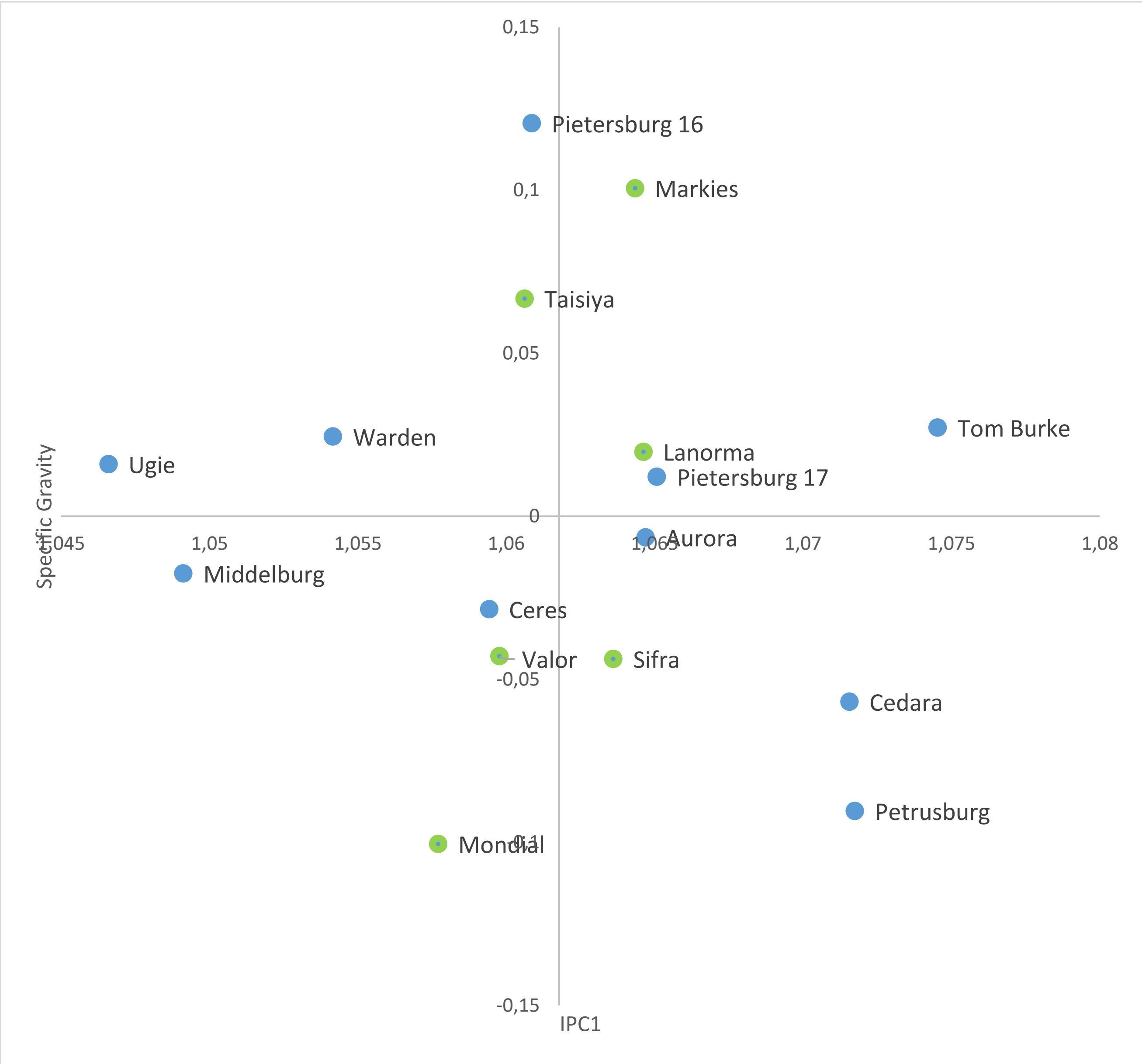

Figure 4-2: AMMI for specific gravity of environment-cultivar interactions

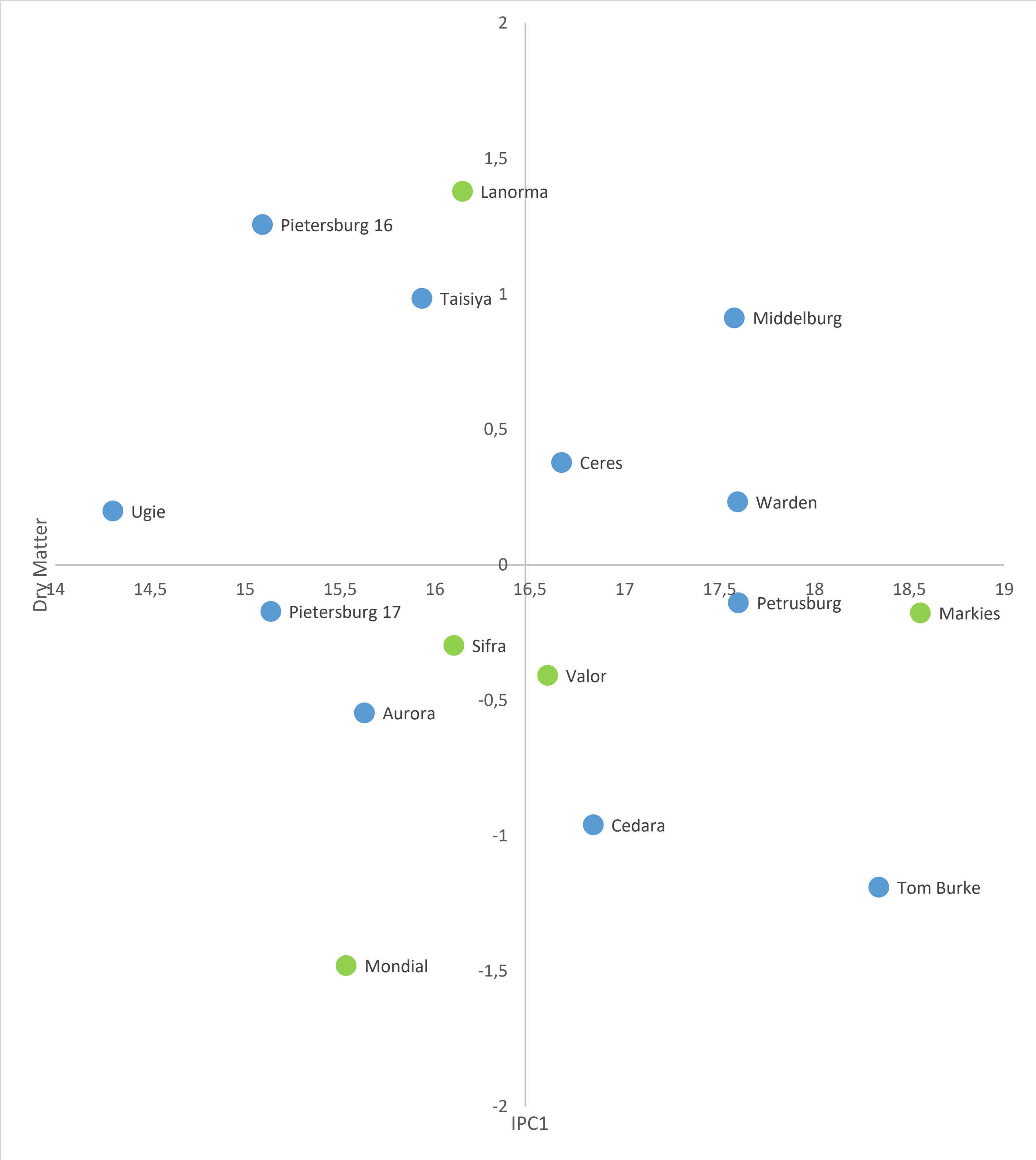

Figure 4-3: AMMI for dry matter of environment cultivar-interactions (not significant)

4.5 Conclusion and recommendation

This data can support farm optimisation which in turn leads to resource use efficiency to deliver high yielding crops. In an attempt to align agricultural actions with the aim to increase nutritious food crop yields, it will be necessary to select appropriate seed cultivars that are adapted to predicted seasonal climate conditions. It is evident that certain cultivars of a specific crop type are better suited to temporal variation and can adapt to biotic and abiotic variables. Intervention strategies of this nature can attempt to increase yields at a faster pace than that of population growth.

External factors have a significant effect on the internal quality attributes of potatoes. Specific gravity, dry matter and chipping colour were three internal quality attributes, which were explored in this study. External factors that were measured did not have a noteworthy effect on chipping colour while specific gravity and dry matter differed significantly between cultivars and over regions.

The unpredictability of the agricultural sector, as well as the occurrence of unforeseen weather events can have dramatic impacts on internal quality attributes of crops. However, certain aspects and tuber specific characteristics remain the greatest influencers of internal quality attributes.

This study showed that certain cultivars delivered more consistent results under varying external conditions i.e. Lanorma, Valor and Sifra. The internal quality attributes of cultivars Mondial, Taisiya and Markies were influenced to a greater extent by the external conditions.

An overall finding was that the environment had a greater effect on the internal qualities of the tubers than the specific cultivar type. Therefore, cultivars are not the main predictor of internal quality attributes, but environmental factors appear to play the major role. Textural classification needs to be done according to area/harvested specific tuber characteristics rather than only using cultivar as a predictor of culinary outcomes.

Being able to predict the effect that certain agricultural environments have on the internal quality attributes of tubers can act as a predictor for outcomes and can, therefore, be used to advise this agricultural sector on action plans that will ensure that the highest quality crop is produced in accordance with external factors.

Efforts should be made to mitigate climate risk, while considering climate resilience. With the currently observed rise in climate risk, resilience must be integrated through calculated and effective reactions to external factors.

This study shows that cultivar classification may not be the ideal way to classify potatoes as environment has a greater effect on textural properties than intrinsic cultivar characteristics.

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Chapter 5: The reliability of dry matter, specific gravity, starch and glycaemic index to classify potatoes

"You ask what is the use of classification, arrangement, and systemization? I answer you: order and simplification are the first steps toward the mastery of a subject – the actual enemy is the unknown."
– Thomas Mann

Abstract

There is a global increase in the production, processing and consumption of potatoes, especially in developing countries. The scale of the different varieties available today has led to a demand by end users to have some indication of fit for purpose. Reliable, scientifically validated objective methods are needed to group potatoes to develop such a system. The reliability of specific gravity, dry matter and starch content as well as glycaemic index were determined as these measurements are often used to describe tuber characteristics. However, the reliability of these methods differed within and between studies. Dry matter content was found to be the most robust analytical method to group potatoes together. Specific gravity proved to be an unreliable method due to the lack of standardisation of the method. Glycaemic index delivered different results using a single cultivar in an inter-laboratory study.

5.1 Introduction

Potatoes form part of diets in various regions and cultures and have solidified their role as a staple crop in diets. These multifaceted nutrient dense tubers have numerous roles to play contributing not only to the nutritional status, but also the fiscal status for up- and downstream i.e. farming and processing in different sectors. Over the last decade a steady increase in the consumption of potatoes and their derivatives occurred, which contributed to the fact that potato crops are one of the most rapidly growing commodities in the agricultural industry (Penn State University, 2013). Globally there are more than 4 000 *Solanum tuberosum L.* species grown commercially, as well as in the wild (International Potato Center, 2015). New potato cultivars are constantly being developed to address constraints as they arise in the agricultural sector. Some of the major factors that are currently considered in breeding programs are: disease resistance, increased yield, locality-specific adaptions and production for consumer-specific markets. The existing potato catalogue, comprising of tubers of varying shapes, colours, chemical compositions and textural qualities is expanded with the introduction of new outcome orientated varieties (Mori, et al., 2015). These new varieties are able to adapt to changing weather conditions, changing agricultural practices, innovations and locality variance that is experienced due to geographical location. All these factors contribute to make tubers a global sustainable crop.

Due to the magnitude and diversification of the crop and its multifaceted role in human diets, systems or groupings are desirable to make is easier for the end user to identify which cultivar or batch would be best for their purpose. Such batch or cultivar specific classification systems are used globally to classify potatoes into textural, processing or health related classes (Pinhero, et al., 2016). Potato classification systems are unique to each country as varieties are dictated by agronomical conditions. In 2012, a revised potato classification system was implemented in the United Kingdom. This system classified potatoes for culinary application; fluffy potatoes are ideal for baking, salad potatoes are best when boiled and smooth potatoes are best when preparing mash (National Potato Council, 2014). In contrast to the cooking method classification of the UK, potatoes in America are classified according to colour and shape i.e. round white, long white, red, yellow, blue, purple and Russet Burbank with little attention given to their specific culinary applications (United States Potato Board, 2018). The new South African potato classification system, as introduced in 2012, groups potatoes into three textural groups. Waxy potatoes are ideal for boiling as they keep their shape, floury potatoes should be used to prepare mash as they deliver a smooth end product and waxy/floury potatoes can be used for all applications. The classification system relied mostly on trained sensory panel analysis (Potatoes South Africa, 2018).

Sensory panel analysis is a preferred measurement for textural classification and eating quality. However, this is an expensive and time consuming method (Chen & Opara, 2013). Therefore, objective measures such as specific gravity (which formed part of the South African potato classification system), dry matter and starch analysis are frequently used to develop and categorise batches of potatoes accordingly (Potatoes South Africa, 2011). These objective measures are focused on determining the internal textural properties of tubers by means of the ratio of dry matter to moisture in the tuber (Thybo, et al., 2000). However, contradictory results have been reported for studies using these methods (Fernando & Slater, 2010).

From a nutritional point of view potatoes are mostly comprised of carbohydrates that can exert an effect on glucose levels in the human body. It has, however, been reported that different cultivars have different glycaemic loads. Glycaemic index and glycaemic load measures are thus also considered methods which could classify potatoes from different cultivars into different categories based on their ability to raise blood glucose levels (Lovat, et al., 2015). However, the analytical method used for *in vivo* glycaemic index analysis contains a variety of intricate steps, which together with external influences can have an effect on the reliability of the end results (Venn & Green, 2007).

The South African potato crop is made up of a variety (more than 80) of cultivars grown in over 16 different production regions using suitable agronomical practices (Potatoes South Africa, 2018). Although technically a vegetable, this tuber is seen as one of the starchy staple foods of the South African population, together with the other staple foods such as maize meal porridge, bread and rice (BFAP, 2019).

5.2 Objective

The purpose of this study was to determine whether (1) dry matter, specific gravity and starch are reliable predictors of potato texture, and (2) if the glycaemic index and glycaemic load are reliable methods to classify potatoes, based on their ability to raise blood glucose levels in humans.

5.2.1 The determine whether dry matter, specific gravity and starch are reliable predictors of potato texture

5.2.1.1 Methodology

The scope and variety of potatoes planted in South Africa in the different climatic regions has necessitated broad data gathering over an extensive period of time to ensure that a representative sample is obtained. For this paper, data from three different studies on specific gravity, dry matter, starch and one study on glycaemic index (which will be discussed separately), were gathered and evaluated. The original data from all three studies were collated into Excel spreadsheets and evaluated using statistical analyses. Due to the individual nature of the different datasets, the methodology used for each dataset was unique and will be discussed in detail in the appropriate section.

5.2.1.2 Dry mater, specific gravity and starch

To test if dry matter, specific gravity and starch are reliable methods to categorise potatoes, a meta-analysis was conducted using the results of three studies. Data on specific gravity, dry matter and starch (refer to Table 5-1 for methods) was compared to sensory profiles in an attempt to evaluate if these measures are reliable when categorising potatoes according to their sensory cooking qualities.

For the first study, data from six production regions for ten potato cultivars was used (Van Niekerk, et al., 2016). The tubers from these trials underwent a variety of objective tests over a three-year period. Tubers and regions with the most repeats were selected to enable statistical evaluation (Table 5-3).

In the second study, data from eleven different cultivars planted in one production region was obtained and analysed (Van Niekerk, et al., 2016). For this study the specific gravity and dry matter values for eleven different cultivars were determined. These tubers underwent objective analysis of dry matter, starch and specific gravity (Table 5-4).

For the third study, data from four separate trials conducted over five regions on eleven different cultivars was compared (Leighton, et al., 2010). Data was statistically analysed to determine which attributes best declared variance in the data for specific gravity, starch and dry matter.

Table 5-1: Analytical methods used for relevant objective analysis

Analysis	Method
Starch	Enzymatic spectrophotometer (In-house method)
Dry matter	AOAC, 2000. Official method of analysis 934.01 (Giron, 1973)
Specific gravity	$Specific\ gravity = \frac{Weight\ in\ air}{(Weight\ in\ air - Weight\ under\ water)}$ (South African Department of Environment and Primary Industries, 2000)

5.2.1.3 Statistical analysis

The data gathered in Micro Soft Excel spreadsheets was inspected for outliers using a residual test. It was subsequently analysed using the GenStat for Windows (2008) statistical computer programme (Payne, et al., 2012). For the first study, a Restricted Maximum Likelihood (REML) analysis was performed over cultivars between regions and over regions between cultivars to determine whether certain objective tests can indicate textural differences in different cultivars over the different regions at a 5% level of significance. For the second and third studies, a Partial Least Squares regression procedure (PLS) of GenStat was used. In study two, a PLS was used to establish the correlation between the set of objective measures (Payne, et al., 2012). A correlation of 0.8 and higher indicates a significant correlation and a correlation of 0.6 and higher indicates a fair correlation (Schippers, 1976). For the third study, PLS was applied to analyse the relationship between objective test measurements and sensory evaluations, with the objective of determining which attributes best describe variance in the data.

5.2.1.4 Results and discussion

Study one showed significant differences in specific gravity between all cultivars over regions except in a single region, namely Loskop Valley (Limpopo province). Significant differences in specific gravity values were seen in the Almera cultivar over the different regions (Table 5-2). It was concluded from this study that specific gravity was the only consistent indicator of differences between cultivars over regions and was the only objective measure included to evaluate the intrinsic textural properties of the tubers.

Table 5-2: Specific gravity of ten potato cultivars over six regions

Specific gravity							
Region		**Limpopo**	**Mpuma -langa**	**Eastern Free State**	**Western Free State**	**South-West Free State**	**Loskop Valley**
Median	n-value	n=7	n=4	n=6	n=7	n=3	n=4
Cultivar	p-value	p<0.001	p<0.001	p<0.001	p<0.001	p=0.039	p=0.831
Almera	p=0.046	1.060^{a,i,ii}	1.058^{a,i}	1.06^{a,i}	1.058^{a,i}	1.069^{b,i}	-
Avalanche	p=0.751	1.069^{i,ii,iii}	-	1.067^{i,ii}	1.065^{i,ii}	-	-
BP1	p=0.433	1.071$^{i, ii,iii, iv}$	1.077	-	1.071^{ii,iii}	-	-
Darius	p=0.519	-	-	1.085^{v}	1.082^{iv}	-	-
Fabula	p=0.915	1.59^{i}	-	1.058^{i}	1.058^{i}	-	-
Fianna	p=0.295	1.082^{iv}	1.09^{iii}	1.081^{iv,v}	-	-	1.073
Mondial	p=0.591	1.066^{i,ii,iii}	1.062^{i}	1.065^{i}	1.063^{i,ii}	1.069^{i}	1.072
Sifra	p=0.654	1.068^{i,iv}	1.065^{i}	1.067^{i,ii,iii}	1.071^{ii,iii}	-	-
UTD	p=0.161	1.07^{i,ii,ii,iv}	-	1.076^{ii,iv,v}	1.079^{iii,iv}	-	1.069
Valor	p=0.269	1.069^{i,iii}	1.071^{ii}	1.073^{ii,iii,iv}	1.07^{ii,iii}	1.081^{ii}	-

Superscript letters indicate significant differences over regions

Roman numerals indicate significant differences over cultivars

Table 5-3: Specific gravity and dry matter of analysis of eleven different potato cultivars from the Eastern Free State

Attribute	**p-value /unit**	**Cultivars**										
		Mondial	**BP1**	**BP13**	**Darius**	**VDP**	**UTD**	**Flanna**	**Fabula**	**Valor**	**Avalanche**	**Sifra**
Specific gravity	p<0.001	1.06^{ab}	1.07^{bc}	1.068^{bc}	1.073^{bc}	1.062^{b}	1.064^{bc}	1.077^{c}	1.061^{ab}	1.065^{bc}	1.047^{a}	1.059^{ab}
Dry matter	g	22.2	20.1	22.4	26.5	19.3	20.9	27.3	22.6	20.4	19.8	20.4

For study two, a correlation matrix was analysed to determine correlations between dry mater and specific gravity values as presented in Table 5-3. Dry matter and specific gravity correlated less with each other than expected at r=0.6831. Significant differences were observed in the specific gravity values of the different cultivars (Table 5-3).

The third study was completed over two years and consisted of four trials. Sensory and objective tests were conducted in all four trials to determine which measures best explained variance in the data. The first dimension declared variance in the sensory data, while the second dimension declared variance in the objective analysis. Only the objective analysis will be discussed for the purpose of this paper.

Dry matter declared variance in all four trials: r=76.1, r=78.3, r=86.0 and r=72.3 respectively. Starch declared variance in the second dimension in three (Trial 1, 2 and 3) of the four trials: r=58.1, r=67.8 and r=66.5, respectively. Specific gravity declared variance in two of the four studies: r=58.2 (Trial 2) and r=81.0 (Trial 4).

From these four trials it was seen that dry matter and starch were the best predictors of variance in data between the different regions over cultivars. Dry matter and starch delivered more consistent results than specific gravity analysis.

Significant differences were seen in the specific gravity between cultivars over all the regions in all four trials. Dry matter between cultivars differed significantly over the different cultivars in Trials 2, 3, and 4. Starch values between cultivars showed differences in three of the trials; 1, 2, and 4. Climatic and agronomical differences in the different regions may be the main influencers of difference seen in the objective values of the different cultivars. It was found that tubers that were planted under irrigation tended to have more similar internal textural properties, while tubers planted under dry land conditions tended to elicit their specific cultivar characteristics (Booysen, et al., 2013).

Specific gravity is one of the most common methods used in the potato industry to determine the cooking or chipping quality of tubers by means of internal textural characteristics. Specific gravity determines the total solids content of a potato tuber. This is done by weighing tubers individually as is, followed by an underwater weighing where the tuber is placed in a sieve and submerged in water. Specific gravity is then calculated using the following equation:

$$Specific\ gravity = \frac{Weight\ in\ air}{(Weight\ in\ air - Weight\ under\ water)} \quad \text{(Eq 1)}$$

(South African Department of Environment and Primary Industries, 2000)

Specific gravity measurements are performed according to equation 1 with no standardised scientific measure, which makes this a fairly easy method to apply as it requires minimal effort and equipment. This is, however, not a robust objective measure as there are a variety of external influences that can have a significant impact on the values, such as water temperature, time elapsed between measurements, age of the tuber and reliability of the equipment and the researcher, to name but a few. All of these variables can influence the reliability of the method to predict classification (South African Department of Environment and Primary Industries, 2000).

Table 5-4: Least square mean values of the objective tests

Least square mean values of objective tests (n=5)											
Cultivars	**p-value**	**Mondial**	**BP1**	**UTD**	**VDP**	**Caren**	**Fabula**	**Valor**	**Buffelspoort**	**Fianna**	**Darius**
Trial 1											
Specific gravity	<0.001	1.05^{d}	1.07^{bc}	1.08^{ab}	1.07^{bc}	1.08^{a}	1.06^{c}	-	-	-	-
Dry matter	<0.001	17.54	22.04	23.44	19.48	16.27	16.72	-	-	-	-
Starch	<0.001	12.02^{bc}	15.28^{a}	15.70^{a}	12.60^{b}	9.45^{d}	11.45^{c}	-	-	-	-
Trial 2											
Specific gravity	<0.001	1.051^{b}	1.079^{a}	-	-	1.074^{a}	-	-	1.055^{b}	-	-
Dry matter	<0.001	17.70^{c}	18.98^{b}	-	-	19.23^{a}	-	-	13.21^{a}	-	-
Starch	<0.001	81.20^{a}	80.53^{a}	-	-	79.59^{a}	-	-	69.03^{b}	-	-
Trial 3											
Specific gravity	<0.001	1.047^{d}	1.054^{bc}	-	1.052^{cd}	-	-	-	1.057^{abc}	1.061^{a}	1.059^{ab}
Dry matter	<0.001	12.24^{f}	14.54^{e}	-	16.65^{c}	-	-	-	16.94^{b}	16.40^{d}	19.61^{a}
Starch	<0.001	7.8^{d}	8.62^{cd}	-	11.18^{c}	-	-	-	10.76^{c}	60.03^{a}	14.99^{b}
Trial 4											
Specific gravity	<0.001	1.0513^{b}	1.0693^{a}	-	-	-	-	1.0673^{a}	-	-	-
Dry matter	<0.001	15.7^{c}	18.74^{a}	-	-	-	-	16.58^{b}	-	-	-
Starch	0.110	10.71	12.77	-	-	-	-	11.79	-	-	-

Superscript letters indicate significant differences between cultivars

As specific gravity measurements are relatively simple to perform, they are more often the chosen method of evaluation. Yet, dry matter is considered a more reliable method, as it is a scientifically repeatable objective analytical method of evaluation (Fischer, et al., 2002). This may be the reason why dry matter analysis in study three delivered consistent results more often than the results obtained with starch content or specific gravity determinations.

Dry matter analysis is a robust standardised analytical method that is recognised internationally according to AOAC 934.01 (AOAC, 2000). Dry matter is measured by drying a known wet weight of finely grated tuber, placing it in a drying oven to extract all the moisture from the flesh and then weighing it again to determine the total dry matter content (Fischer, et al., 2002).

Starch analysis on the other hand, which is commonly used as an in-house method, is an intricate process that consists of many steps where errors can occur. Starch was measured by means of an enzymatic method. The enzymes used in the analysis of starch are another variable that can lead to discrepancies in the data. Enzymatic reactions can differ if the enzymes used are old or inappropriately used. Starch analysis is described as a "quite difficult" and even when completed, can only deliver reasonably accurate data (Greenfield & Southgate, 2003).

Due to the regional factors that affect tuber qualities (Booysen, et al., 2013), it was already proposed in 1976 that region-specific measurements and classification systems be applied in the potato industry in the United Sates. A series of studies were published in the American Journal of Potato Research between 1956 and 1970 on the relationship between specific gravity and dry matter (Houghland, 1966). A noteworthy number of these studies found that the relationship between dry matter and specific gravity measures were not stable enough to be used as a standardised method (Nissen, 1967). However, limited studies were published in later years indicating no real resolution or conclusion of the matter.

In an attempt to rejuvenate the correlation charts of dry matter and specific gravity, Oregon State University developed a specific gravity and dry matter reference guide which indicates the relationship between specific gravity and dry matter. The guide allows for specific gravity values that range from 1.055 to 1.095, with correlating dry matter values of between 16.5%-24% (Fernando & Slater, 2010). But in a study conducted in Pakistan, the specific gravity values of 32 different cultivars of potatoes were found to vary between 1.0343-1.1443 (Abbas, et al., 2011). which is a wider range than the average values seen in European and American potatoes. This can be due to different cultivars and agronomical methods that are used in different countries and provides motivation to test the reliability of these methods for classification of different potato cultivars in South Africa as well.

The assumption that dry matter is a linear function of specific gravity should thus not be considered scientifically validated (Sani, 1964). A tuber's texture is mainly determined by the ratio of dry matter to moisture found in the tuber. The higher the dry matter content, the lower the water content, which means that such a potato has a higher specific gravity. Potatoes with a higher dry matter and low moisture content are mealy, ideal for baking, and potatoes with a low dry matter content and a high moisture content are waxy and ideal for boiling (South African Department of Environment and Primary Industries, 2000).

In contrast with the second study, which found a weak correlation between specific gravity and dry matter, a study conducted in 1975 on 1 269 tubers in America indicated that there was a strong correlation (r=0.912) (Schippers, 1976). The Pakistan study mentioned above, reported a correlation of r=0.5966 (Abbas, et al., 2011). These differences in correlation may be due to different cultivars and agronomical methods that are used in different countries, as well as the method used to analyse specific gravity. This discrepancy in correlations can undermine the validity of superimposing specific gravity values on to dry matter values. In most cases, these values correlate by less than 80%.

5.2.2 The determine whether glycaemic index and glycaemic load are reliable methods to classify potatoes based on their ability to raise blood glucose in humans

5.2.2.1 Methodology

In order to determine the validity of using the glycaemic index (GI) as a method to categorise potato cultivars into classes based on their ability to raise blood glucose, a three step proses was followed. Firstly, to determine the GI, as well as the glycaemic load (GL) of any food, the amount of carbohydrate such a food contains needs to be determined. Nutrient analysis (Table 5-5) of selected nutrients (energy, carbohydrate (by difference), protein, fat, moisture and ash) was done at the ARC-Irene Analytical Services. The laboratory is accredited by the South African National Accreditation System (SANAS) (Giron, 1973). GI Testing was done by the GI Foundation SA. Both laboratories conducted their trials according to international protocol (as recommended by an International Expert Consultation on Carbohydrates in Human Nutrition) (Food and Agriculture Organization/World Health Organization, 1998), the recommendations of the International Life Science Institute (ILSI) appointed International Committee for Standardization of GI Testing Methodology and the draft regulations of the South African Department of Health pertaining to GI testing methodology (Brouns, et al., 2005). All methods and calculations were performed according to ISO 26642 (ISO 26642, 2008).
For the second step the GI values of Almera potatoes, cultivated and transported under controlled conditions, were determined at two laboratories performing two trials (ISO 26642). During the first trial (Laboratory A, Trial 1), the potatoes were cooked and allowed to cool before consumption. During the second trial (Laboratory A, Trial 2), the potatoes were consumed warm. Laboratory B performed both tests on warm samples, but used different panel members in the second trial (Laboratory B, Trial 2), than in the first trial (Laboratory B, Trial 1). This method was followed to determine whether results obtained from the different laboratories correlated with one another to evaluate the reliability of GI testing to deliver consistent results.

All the subjects used in this study participated in a glucose test with either maltose or white bread (GI 100) on at least two, but preferably three, different occasions in order to obtain a reference value for each individual subject. The margin of error in GI determinations decreased substantially when 2 measurements, rather than only one measurement of the reference food were used, when data from the inter-laboratory study was used by researchers (Brouns, et al., 2005).

In the third and final phase of this study the results obtained from the glycaemic tests done at the different laboratories were compared to international data to determine whether the values are internationally comparable.

5.2.2.2 Results

In Table 5-5 the results of the first step of the study show selected nutritional values for the Almera potato. The carbohydrate value was used to determine the GL of the samples. GL was calculated according to the prescribed equation (Eq 2):

$$Glycaemic\ Load = Carbohydrates \times \frac{Glycaemic\ Index}{100} \quad \text{(Eq 2)}$$

(Foster-Powell, et al., 2002)

Table 5-5: The nutritional composition of raw potatoes (g/100g)

	Moisture	Fat	Protein	Carbohydrates	Fibre	Ash
Almera (raw with skin)*	86.3	0.07	2.24	9.46	1.02	0.93
Potatoes (raw with skin)^	80.2	0.10	1.50	15.9	1.50	0.90

* Own data obtained at ARC-Irene Analytical Services (2013)
^ Food Composition Database, 1999

The GI and GL values obtained from the second step in the study are shown in Table 5-6. The confidence interval (CI) indicates that the researcher can be 95 % confident that the GI value of the specific product will lie between the bottom and the top values presented. The mean GI value of Almera potatoes was found to be 43, with an average GL value of 4.07, which classifies this product as a low GI food (GI $\leq$ 55). In Laboratory A, Trial 1, the GI values for Almera potatoes were between 33 and 52. In Laboratory A, Trial 2, the GI values were between 86 and 35 with an average of 63 and a GL value of 5.96, which classifies this product as a medium GI food (GI 56 -69).

Laboratory B, Trial 2, produced an average GI of 84 and Trial 2, produced an average GI of 96. Both trials had a standard deviation of 21, which shows noteworthy differences between the different subjects. These GI values place the Almera potato in the high GI class (70>). These values from laboratory B compared with the value for baked potatoes in the South African Glycaemic Index and Load Guide at a GI of 85 (high GI) (Steenkamp & Delport, 2005).

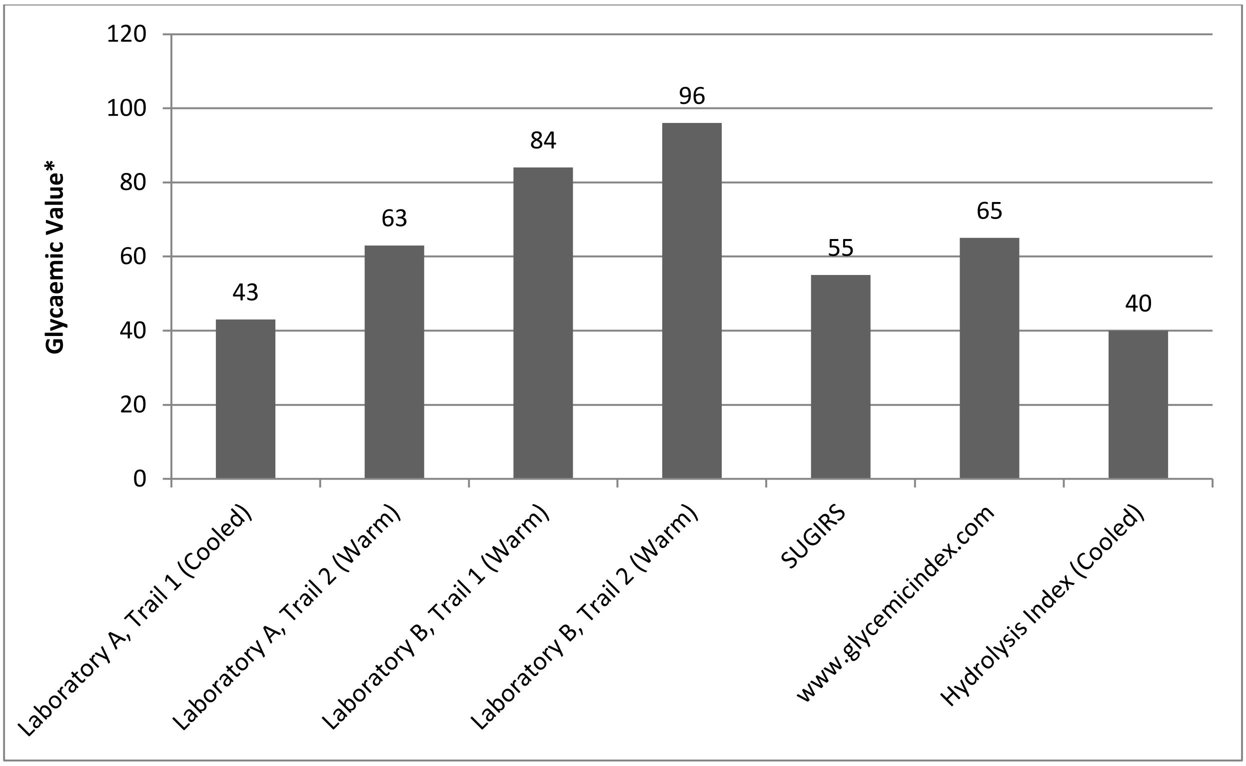
The final step in the study was to compare the data obtained from the trials of the two laboratories with international data. For this part of the study the South African values were compared to those of the Sydney University Glycemic Index Research Service (SUGIRS) (Atkins & Brand-Miller, 2006) (Figure 5-6).

Differences were seen in the GI values between both laboratories and all four of the trials. It can be clearly seen that the GI values from Laboratory B were significantly higher than the values obtained from Laboratory A (Table 5-6 and Figure 5-1). The data obtained in the second trial at Laboratory A also produced results which were similar to the results published on the electronic database of the Australian GI website (Glycemic Index, 2010) (Figure 5-1).

Table 5-6: Glycaemic Index and Glycaemic Load values for Almera potatoes from two different laboratories

	Laboratory A				Laboratory B			
	Trial 1 (cooled potatoes)		Trial 2 (warm potatoes)		Trial 1 (warm potatoes)		Trial 2 (warm potatoes)	
Subjects	**GI**	**GL**	**GI**	**GL**	**GI**	**GL**	**GI**	**GL**
GI Mean	43	4.07	63	5.96	84	7.95	96	9.08
SD	14	1.32	18	1.70	21	1.99	21	1.99
95 % CI (lower)	33	3.12	50	4.73	-	-	-	-
95 % CI (higher)	52	4.92	76	7.19	-	-	-	-
Subject 1	46	4.35	51	4.82	125	11.83	98	9.27
Subject 2	28	2.65	81	7.66	99	9.37	121	11.45
Subject 3	29	2.74	85	8.04	126	11.92	130	12.30
Subject 4	47	4.45	61	5.77	67	6.34	75	7.10
Subject 5	54	5.11	86	8.14	51	4.82	77	7.28
Subject 6	53*	5.01*	45*	4.26*	72	6.81	98	9.27
Subject 7	61*	5.77*	35*	3.31*	98	9.27	97	9.18
Subject 8	27	2.55	46	4.35	85	8.04	79	7.47
Subject 9	55	5.20	64	6.05	86	8.14	137	12.96
Subject 10	21*	1.99*	76*	7.19*	57	5.39	74	7.00
Subject 11	-	-	-	-	60	5.68	83	7.85
Subject 12	-	-	-	-	80	7.57	87	8.23
Subject 13	-	-	-	-	82	7.76	90	8.51
Subject 14	-	-	-	-	-	-	70	6.62

*Non-Insulin Dependent Diabetes Mellitus (NIDDM)



*A food with a glycaemic index value greater than or equal to 70 is considered to have a high GI, lower than or equal to 55 is considered to have a low GI, and a value between 70 and 55 (or from 56 – 69) is classified as an Intermediate GI food.

Figure 5-1: Glycaemic Index values obtained for cooked Almera potatoes

5.2.2.3 Discussion

Various factors influence the GI of a food product including product characteristics such as cultivar, growing conditions, preparation method and some more. Further, the method used to determine GI could also impact significantly on the GI reading which is obtained.

The glycaemic index is expressed as a percentage of the response to 50 g of carbohydrate of a standard (reference) food taken by the same subject, on a different day. This reference food is usually either white bread or maltose or even both. Until recently the effect of food on blood sugar levels was determined by the carbohydrates in the food. The glycaemic index is seen as a more reliable method to determine the effect of food on blood glucose levels. The glycaemic index is expressed as a number between 1 and 100 depending on the rate of carbohydrate absorption (Cummings & Stephan, 2007). The lower the rise of blood glucose level, the lower the glycaemic index of a food. The hydrolysis index was obtained by dividing the area under the hydrolysis curve of each sample by the corresponding area of a reference sample (FAO/WHO, 1998).

There are also a few factors that have an influence on GI values obtained from human subjects. Firstly, it is essential to note that human subjects vary, however, this is taken into consideration as the effect of the food on blood glucose values is compared to the effect of a reference food, e.g. glucose or white bread on blood glucose values in the same individual. Secondly, many factors, including emotional and stress factors, which cannot be controlled, may also play a significant role in influencing glycaemic response (Cummings & Stephan, 2007). It thus becomes important to ensure that the person is subjected to the same conditions when performing the reference test (i.e. glucose), as when testing a specific food.

There is also a large variability in glycaemic response between different individuals (Frost & Dornhurst, 2000). In a study which included healthy individuals, non-insulin treated Non-Insulin Dependent Diabetes (NIDDM), insulin-treated NIDDM and Insulin Dependent Diabetes (IDDM) subjects, it was found that the coefficient of variation (CV) values between individuals from each group were 26%, 34%, 23% and 34% respectively (Wolver, et al., 2008). This adds up to a mean inter-individual CV of 29%.

Earlier work by Coulston noted that by expressing the glycaemic response to a test food as a comparison of the response to a reference food, the variation in GI that occurs for age, sex, body composition, ethnicity and medical conditions should be accounted for (Coulston, et al., 1984). A similar study (Jenkins, et al., 1981) found that by expressing glycaemic results in this way, reduced the inter-individual CV from 40% to 10%.

Although expressing values as a percentage compared to the response to a control food reduced inter-individual variation, studies have shown the GI measurements of the same food vary greatly between individuals (Frost & Dornhurst, 2000). Although GI was calculated as stated above, a later study found (Matthan, et al., 2010) that variability in GI values can still in part be explained by differences in age. Another study (Hollenbeck, et al., 1986) found that the GI values of lentils range from 23 to 70 for different subjects. It is furthermore suggested that this variation in results obtained between individuals can be reduced when both the food to be tested and the control food are measured in triplicate for each panellist (Frost & Dornhurst, 2000). However, this is not done in practice, as the costs involved would be exorbitant.

As a high degree of variation was observed in this study between individuals in the initial GI test at Laboratory B (SD > 20), it was prudently decided to repeat the analysis in both laboratories. The inclusion of an additional 14 individuals in the second Laboratory 2 trial did not alter the GI of the test food in such a way as to change the GI category into which the food was ultimately classified.

The Sydney University Glycemic Index Research Service (SUGIRS) was established in 1995 to provide a commercial GI testing laboratory for the international food industry. According to Dr Alan Barkley of SUGIRS, their laboratory tested the GI of the Almera potato cultivar on eight different occasions. The results from these trials varied from 40 to 69, with a mean GI value of 55. For each test, the potatoes used for the samples were grown under slightly different conditions. In Dr Barkley's opinion the Almera cultivar, when grown under the correct conditions and cooked appropriately, would have a low GI (Barkley, 2010). The values obtained from SUGIRS differed to those seen in this paper of 43 for Laboratory A, Trial 1; 63 for Laboratory A, Trial 2; 84 for Laboratory B, Trial 1 and 96 for Laboratory B, Trial 2.

Due to all the factors that can have an influence when measuring the glycaemic index of food *in vivo* the reliability of this method to classify potatoes into categories warrants further investigation as reliability seems limited.

5.3 Conclusions and recommendations

From study one, two and three it can be concluded that dry matter, starch and specific gravity are objective measures that can be used to classify potatoes into textural classes. However, specific gravity did not deliver consistent, correlating results. Dry matter is the most robust method and was shown to be the most reliable method to correlate with the internal textural properties of potato tubers.

Significant differences were found between GI values and more specifically, GI categories (low, medium and high GI), obtained from different laboratories executing *in vivo* analyses on the Almera potatoes. This can lead to questions about the reliability of the method, as well as the accuracy with which it is performed at the different laboratories.

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Chapter 6: Classification of potatoes using a boiling test

"The same boiling water that softens the potato hardens the egg. It's about what you're made of, not the circumstances." - Unknown

Abstract

Classification of a cultivar according to the current potato classification system is a complex process that is time consuming and expensive. Potatoes are currently classified according to cultivar as being either waxy, waxy/floury or floury. This classification provides a general guideline for the ideal way to prepare a specific potato cultivar. Various other factors such as weather conditions and cultivation practices have, however, been noted to significantly alter the anticipated textural qualities of tubers. This difference in prediction and result often leads to consumer dissatisfaction.

A need for a cost-effective, high-value methodology was therefore identified, which could differentiate between potato cooking types. This method needs to be easily repeatable and reliable on a farm level for batch specific classification of potatoes.

An easy-to-follow and standardised cooking method was developed. Both boiling and baking methodologies were tested based on their ability to consistently and visually illustrate the internal textural properties of the tubers.

By means of a five step process a standardised cooking method and visual guide was developed which can be used to classify potatoes into textural classes on a batch specific level.

6.1 Introduction

More than a billion people eat potatoes on a daily basis making potatoes the fourth largest food crop and one of the most extensively consumed root vegetables on earth (Ek, et al., 2014). More than 4 000 *Solanum tuberosum L.* species are grown commercially, as well as in the wild, so that potatoes are capable of fulfilling the dietary needs of many different cultures (International Potato Center, 2014). At the beginning of the new century, the global per capita consumption of potatoes reached a new height of 33kg/pp. It is estimated that this figure will rise steadily in the coming years (King & Slavin, 2013; Krieger, 2010). The above mentioned high consumption figure and the predicted increase in consumption have ensured that potatoes play a role in the rapidly growing agricultural sector, and contribute to global economics and food security (Devaux, et al., 2014; Vreugdenhil, et al., 2011).

Potatoes are such a diverse crop, that quality parameters for consumer preferences and classification are difficult to determine and predict. According to the literature, some of the most reliable quality attributes which can be used to define potatoes are internal colour, intensity of aroma, mustiness, earthiness, hardness, adhesiveness, moistness, sweetness and aftertaste. These have been found to be some of the main characteristics by which consumers evaluate potatoes (Thybo & Martens, 2000). However, not one of these attributes can be singled out as a quality marker since the most dependable one is determined by the preference of the individual consumer, which may be taste texture or appearance, as well as the adherence to fulfil expectations in terms of classification guidelines (Clark, et al., 1940). Furthermore, it must be acknowledged that texture is a multi-parameter attribute. This makes pinpointing specific potato characteristics for consumer preference and classification purposes a difficult task (Szczesniak, 1991).

Potato characteristics and internal quality can be significantly influenced by biotic and abiotic variables. Significant differences can be observed in potatoes grown under varying environmental conditions (e.g. climate, agricultural practices) (Svubure, et al., 2015). Thus, the global sporadic weather phenomena that are currently occurring may have a significant effect on potato production and crop losses. Not only do these weather changes have an effect on yield, but also on the internal quality aspects of the crop which further complicates classification practices (Hagman, et al., 2009).

Changing weather patterns and agricultural circumstances necessitate a need for the development of new cultivars. New cultivars are bred in such a manner that they are less prone to certain diseases and are more adaptable to specific agronomical and geographical variances and are even able to adhere to specific internal characteristic requirements. These changes in production practises, together with the drive for consumer satisfaction, in terms of the appearance of, and cooking qualities of potatoes, contribute to the uniqueness of the industry, but also necessitate the need for flexibility within classification systems (Kleinwechter, et al., 2016; Thybo & Martens, 2000).

The multiple parameters that affect internal textural characteristics, as perceived by consumers and as required by the secondary industry, consisting of processors and resellers to name a few, contribute to the complexity of potato classification. The non-homogenous nature of biological products is further influenced by the external environment, which can lead to further variations between batches. Therefore, a variety of potato guides and classification systems exists globally to classify potatoes at a batch specific level. In 2014, Potatoes New Zealand released their 'Cook test guidelines for fresh potato retail sales'. The purpose of this guide was to ensure accurate labelling, which in turn would lead to customer satisfaction and repeat purchase of potatoes as the starch choice for meals (Potatoes New Zealand, 2016). The need for such a guide was identified because buyer dissonance was experienced, which was attributed to misleading packaging (Wilkins, et al., 2016).

Due to the magnitude and diversification of the crop and its multifaceted role in human diets, systems or groupings are required to make it easier for the end user to identify which cultivar or batch would give the best fit for a given purpose. Such batch or cultivar specific classification systems are used globally to classify potatoes into textural, processing or health related classes (Pinhero, et al., 2016). As classification of food is a complex process involving a variety of divergent variables, a simple, quick, easy and affordable solution is required.

The current South African classification system, as developed in 2011, is based on sensory panel analysis together with specific gravity measurements (Potatoes South Africa, 2011). This manner of classification is expensive and time consuming and is difficult to apply at the farm level (Chen & Opara, 2013). An easy and effective, repeatable method was, therefore, proposed to classify batches of potatoes at a packaging and retail level. This guide had to be easily accessible and understandable for all role players in the potato industry.

The urgency of packaging of potatoes after they have been harvested and washed to reach the market further prompts the need for an easy and rapid visual method to classify potatoes into batch specific textural classes for fresh potato retail sales, that can be easily and repeatedly performed by any worker, no matter which skill level he/she has attained.

6.2 Purpose

Development of a science-based, easy-to-use, standardised cooking test and visual guide, which could be used for batch specific classification of potatoes according to cooking quality.

6.3 Materials and methods

Both boiling and baking methods were investigated to visually evaluate the textural properties of potatoes during cooking. Objective measures of dry matter and specific gravity were also performed on the tubers for comparison.

6.3.1 Sourcing and methodology development

Potatoes were sourced from nine production regions, distributed over South Africa (Table 6-1). Tubers were harvested, placed at random in brown paper bags and transported to the laboratory. On arrival at the laboratory, unwashed potatoes were stored in a cool dark room for seven to ten days to replicate market conditions. Potatoes were washed with tap water and dried with paper towels. Specific gravity (SG) measurements were performed in triplicate with three different tubers for each cultivar. Dry matter analyses were performed gravimetrically on a composite sample of three randomly selected tubers of each cultivar at the Agricultural Research Council, Irene.

Dry matter

Dry matter content was determined on selected tubers gravimetrically using the method as outlined by AOAC 934.01 (AOAC, 2000). The results were expressed as % dry mater content.

Specific gravity

Specific gravity was determined by weighing three tubers of each cultivar individually as is, followed by an underwater weighing where the tuber was placed in a net and submerged in water at room temperature (22˚C). Specific gravity was then calculated using the following equation (Eq.1):

$$Specific\ gravity = \frac{Weight\ in\ air}{(Weight\ in\ air - Weight\ under\ water)} \quad \text{(Eq.1)}$$

(South African Department of Environment and Primary Industries, 2000)

Overview of methodology

Potatoes were boiled in tap water in a saucepan on a stove top with an initial temperature of 22˚C (±1˚C) to an end temperature of 96˚C (±2˚C). All the equipment used was standardised prior to each test. All cooked potatoes were photographed and visually scored according to their internal textural properties after cooking. The fork test was applied to each potato to determine whether this is a reliable method for textural evaluation. In order to perform these tests, a cooked potato was pressed with the prongs of a fork. The manner in which the potato breaks or spirals through the prongs of the fork is then noted (IDDSI, 2017). It is assumed that a waxy potato will break into chunks, while a floury potato will protrude through the fork and flatten instead of breaking apart. The fork test was done on potatoes 10 minutes after they had been removed from the water and after they were photographed. The spirals through the fork as well as the way in which the potato broke were noted.

Tubers from all the different studies were photographed and categorised during each one of the steps. Flash cards containing the visual image as well as all the different objective and subjective measurements were made. These cards were used as an easy guide to classify the tubers and to determine whether there are any correlations between the different tests and methods. The final standardised methodology was developed by means of a five step process which is discussed in detail in the following section.

Table 6-1: List of regions and cultivar analyses used in the study.

Regions	**Ugie**	**Kokstad**	**Bultfontein**	**Douglas**	**Tom Burke**	**Pietersburg**	**Middelburg**	**Aurora**	**Ceres**
Cultivars	Mondial	Almera	Almera	F12108	Almera	Almera	Fianna	Almera	Almera
	Sifra	Electra	Electra	Lanorma	Bonata	Crop 34	Lanorma	Fianna	Fianna
		Fianna	Grandeur	Laperla	Crop34	Lanorma	Markies	Lanorma	Infinity
		Grandeur	Innovator	Modial	Electra	Markies	Mondial	Markies	Ivory Russet
		Labadia	Lanorma	Taisiya	Fandango	Mondial	Rumba	Mondial	Lanorma
		Lanorma	Laperla		Farida	Rumba	Sifra	Sifra	Markies
		Laperla	Markies		Georgina	Sifra	Valor		Mondial
		Markies	Monate		Hanna	Valor			Sifra
		Mondeo	Mondial -		Labadia				Taisiya
		Mondial	Mondial +		Lanorma				
		Navigator	Navigator		Liberty				
		Panamera	Panamera		Markies				
		Savanna	Savanna		Mete				
		Sifra	Sifra		Mondeo				
		Taisiya	Taisiya		Mondial				
					Moonlight				
					Mundlo				
					Panamera				
					Savanna				
					Sifra				
					Taisiya				
					Valor				
					Vivie				
n=90	n=2	n=15	n=15	n=5	n=23	n=8	n=7	n=6	n=9

+ with Velum (Velum is a broad spectrum nematicide/fungicide)

- without Velum

6.3.2 Method creation (Step 1)

In order to develop the proposed cooking methods, potatoes were sourced from local supermarkets. Mondial and Sifra were the most readily available and these cultivars were chosen for the evaluation of the boiling and baking methods. For this part of the study the cooking methods were tested and evaluated to determine the ideal cooking times and temperatures.

Boiling

Tubers weighing between 180g and 220g were sliced into quarters and covered in tap water. The water was brought to the boil and tuber samples were allowed to simmer for 30 minutes after which the first internal temperature measurements of the tubers were taken. Thereafter internal temperatures were measured every five minutes until an internal temperature of 88˚C was reached. Tubers were then removed from the water and allowed to cool for 10 minutes and were subsequently photographed and evaluated.

Baking

Whole tubers weighing between 180g and 220g were placed on a baking tray and baked in a pre-heated oven at 180˚C until an internal temperature of 88˚C was reached. Potatoes were removed from the oven and allowed to cool for 10 minutes after which they were sliced in half perpendicular to the core with a sharp knife, photographed and evaluated.

6.3.3 Method development (Step 2)

For the second step in the study, potato cultivars were sourced from Ugie (n=2) (Eastern Cape) and Kokstad (n=15) (Kwazulu-Natal). The cooking test described above was further refined during this step.

Boiling

Potatoes were sliced into quarters, placed in a saucepan and covered with tap water at which point time measurement was started. One quarter was removed after 30 minutes and after that one quarter every 10 minutes at 30, 40 and 50 minutes. Once removed from the water quarters were allowed to cool for 10 minutes after which they were evaluated.

Baking

Potatoes were baked for 1 hour at 180˚C in a pre-heated oven and then removed from the oven. The warm tubers were allowed to cool for 10 minutes after which they were sliced perpendicular to the core and evaluated.

6.3.4 Method testing (Step 3)

For the third part of the study potatoes were sourced from Douglas (n=5) (Northern Cape). This part of the study was used to test the cooking methods.

Boiling

Potatoes were sliced into halves rather than quarters. The halves were placed in a saucepan and covered with tap water and boiled for 30 minutes, after which they were removed from the water and allowed to cool for 10 minutes and then evaluated.

Baking

Potatoes were baked for 1 hour at 200˚C and removed from the oven. The warm tubers were allowed to cool for 10 minutes after which they were sliced perpendicular to the core and evaluated.

6.3.5 Method finalisation (Step 4)

The cooking methods were validated using tubers from Bultfontein (n=15) (Free State) (summer growth season) Pietersburg (n=8) (Limpopo), and Tom Burke (n=23) (Limpopo) (winter growth seasons). Both the cooking and boiling tests were repeated to ensure that consistent results were obtained. The method was finalised using tubers from different growing seasons to ensure that the method was tested and climatic variations were taken into consideration.

Boiling

Potatoes from Bultfontein and Tom Burke were sliced in half, perpendicular to the core, and placed in a saucepan. Tubers form Pietersburg were sliced into quarters. Potatoes were covered with tap water and brought to the boil which took between 9-10 minutes. Potatoes were allowed to simmer for 30 minutes, removed from the water and allowed to cool for 10 minutes after which they were evaluated.

Baking

Whole potatoes were baked in a pre-heated oven at 200˚C for 1 hour, removed from the oven, allowed to cool for 10 minutes, after which they were sliced in half perpendicular to the core and evaluated.

6.3.6 Method validation (Step 5)

A decision was taken to evaluate more than one tuber at a time because tubers of the same plant have different growth rates and are affected by external influences. For this step in the study, tubers from Middelburg (n=7) (Mpumalanga), Aurora (n=6) (Western Cape) and Ceres (n=9) (Western Cape) were used. To ensure reliable results six tubers from each cultivar were subjected to the boiling method. Six tubers were sliced into quarters and one quarter from each tuber was boiled.

Baking

The baking test was not applied to these tubers.

6.4 Results and discussions

Extensive evaluations were used to assess the cooking test. A variety of obstacles was encountered. These obstacles will be discussed below as they were experienced during the different tests.

6.4.1 Boiling test

There was no set standard for the internal temperature of a cooked potato. The literature states that the internal temperature of a cooked potato can range from 75˚C to 97 ˚C (Ek, et al., 2014; Jackson, et al., 2013; Gilsenan, et al., 2010; Oruna-Concha, et al., 2002; Department of National Education, Section Home Economics, 1979). An internal temperature of 88˚C was decided on for the method **creation and development** stage.

During the **method creation** stage, where store bought tubers were used, it was found that tubers took between 45 – 55 minutes to reach an internal temperature of 88˚C. When boiled for such a long period the potatoes tended to fall apart (slough) and lose their cultivar specific integrity making all the tubers appear floury.

During the **method development** stage different boiling times were tested. During this step, tubers were also subjected to simmering water rather than boiling water to avoid tears and breaks in the flesh of the tubers.

During the **method testing** stage a shortened boiling time was tested. Potatoes were covered in tap water which was brought to the boil, this took 9-10 minutes, after which the heat was turned down to a simmer and timed for 30 minutes. The potatoes were subsequently removed from the water and allowed to cool for 10 minutes prior to being photographed. When this cooking process was used an average internal temperature of 71.6˚C was reached. It was discovered that when boiling potatoes for a shorter period of time they maintained their internal structure without disintegrating.

During the **method finalisation** stage it was decided to slice the potatoes into halves and quarters to determine which shape produces the best texture results. It was noted that when the potatoes were sliced in half, the skin of the potato provided support to the flesh. This resulted in the potatoes appearing waxier than the real texture as no cracks formed. It was decided to use quartered potatoes as this gave a more accurate visual representation of the texture through the formation of cracks in the flesh of the potato.

6.4.2 Bake test

A baking test was proposed as a second method of characterisation which could be used together with the boiling test. All baking tests were conducted in a Defy 90cm Stainless Steel Electric oven - DGS161.For the method testing step of the baking test a pre-heated oven at a temperature of 180˚C, which is the recommended heat for baking a variety of household dishes (Department of National Education, Section Home Economics, 1979), was utilized. For these tests tubers were left whole, as exposure to dry heat affects the open surface of the tuber which dries out. The baked potatoes, like the boiled potatoes, were baked to an internal temperature of 88˚C which took up to 1 hour 45 minutes. The same problem was experience as with the long boiling time, namely that the potatoes lost their specific internal structure and had a similar (floury) appearance. Potatoes also dehydrate during this long baking time and develop a crispy skin which pulls away from the flesh, giving a false impression of the textural properties.

During the method testing step the oven temperature was increased to 200˚C and potatoes were baked in the pre-heated oven for 1 hour and removed. These potatoes had an average internal temperature of 77˚C. This was done to ensure that the potatoes started cooking faster, the time was shortened to decrease dehydration and was in line with the cooking method applied in the New Zealand cooking test (Potatoes New Zealand, 2016).

During the method finalisation and validation part of the study it became evident that the baking test does not deliver reliable consistent results. Most cultivars stay intact during the baking process providing inconsequential visual guidance of the textural properties. Therefore, it was decided that baking is not a suitable method for visual textural prediction and differentiation.

6.4.3 Fork test

The fork test was applied to 37 boiled potatoes of different cultivars and from different production regions. It was found that when enough force is applied to the tubers, spirals form through the prongs of the fork irrespective of the texture of the potatoes, giving most of the potatoes a floury appearance. The unreliability of the fork test was brought into question during this part of the study as it did not deliver consistent results especially if performed by different individuals – as will be the case when the test is used in industry.

6.4.4 Objective measures

Dry matter and specific gravity measurements were used together with the visual guide. This ensured that the subjective method could be compared with the objective measures. The objective measures were used as a control to ensure that the results of the visual guide are reliable (Table 6-2). The literature reveals that tubers with a higher dry matter content and a lower moisture content are floury

(Ngobese & Workneh, 2016). Tubers with a high moisture content and low dry matter content tend to be waxy (McComber, et al., 1994). These results were used as a means of validation when visually classifying the different tubers.

Cards showing the tubers as well as the specific gravity and dry matter content were produced. The cards were packed into categories based on the visual appearance of the tubers. Once the tubers were divided into different categories the specific gravity and dry matter values were checked to determine whether they coincided with the visual appearance and proposed classification category.

Although visual appearance correlated with dry matter within a specific batch of tubers and cultivars from a single production region, dry matter was inconsistent for cultivars across regions. This further supports the premise that a classification method is required for batch specific classification.

6.4.5 Flash cards

A batch of flash cards with each card featuring a tuber's image, dry matter and specific gravity measurement, as well as any other tuber specific information that was captured during the cooking process, was created for each step in the process. During the method creation and development step no clear differences were seen between the different cultivars. In the method testing step, where different boiling times were applied it became evident that after boiling tubers for 30 minutes, which did not always result in them being cooked, their intrinsic characteristics appeared as cracks in the flesh of the tuber. During the method finalisation and validation step it was found that the cracks correlated with the texture and to some extent with the dry matter content of the tubers. Waxier potatoes, with a lower dry matter content, had fewer cracks, while floury potatoes, with a higher dry matter content, exhibited more cracks and sloughing.

6.4.6 Cooking guide

When all of these factors are taken into consideration, a final boiling test can be proposed. This boiling test ensures that tubers deliver consistent results and provides a clear guide to of the textural properties of the specific potato.

The boiling test:

1. Select 6-8 potatoes (+/-200g each) from a batch
2. Wash and dry the potatoes
3. Slice potatoes into quarters and use one quarter from each tuber
4. Place the potatoes into a saucepan and cover with tap water
5. Bring to the boil (it takes about 10 minutes)
6. Turn the heat down and allow to simmer

7. Cook potatoes for another 30 minutes
8. Remove potatoes from the water and allow to cool for 10 minutes prior to visual evaluation

6.4.7 Final visual guide

Tubers can be categorised based on the numbers and position of cracks that appear in the flesh. **Waxy** potatoes, have no cracks after being boiled, **waxy/floury** potatoes have one crack, most commonly in the middle of the tuber, **floury** potatoes, have two to three cracks, which appear in the middle as well as along the side wall of the potato and lastly the **processing** group. The processing potatoes slough during the cooking process, while cracks appear all along the wall of the potato (Table 6-3).

Table 6-2: Dry matter and specific gravity values of Tom Burke, Bultfontein, Douglas, Pietersburg, Middelburg, Aurora and Ceres potatoes.

	Tom Burke (C-W)		Bulfontein (W-C)		Douglas (W-C)		Pietersburg (C-W)		Middelburg (C-W)		Aurora (C-W)		Ceres (C-W)	
	DM%	**SG**	**DM%**	**SG**	**DM%**	**SG**	**DM%**	**SG**	**DM%**	**SG**	**DM%**	**SG**	**DM%**	**SG**
Valor	20.35	1.073	*	*	*	*	14.74	1.056	17.63	1.047	*	*	*	*
Sifra	18.62	1.062	16	1.064	*	*	13.67	1.055	17.35	1.051	14.57	1.064	16.71	1.056
Taisiya	14.96	1.063	14.48	1.051	17.52	1.068	*	*	*	*	*	*	17.14	1.056
Lanorma	18.6	1.071	15.05	1.061	14.37	1.059	16.03	1.065	19.78	1.059	15.63	1.062	17.24	1.058
Markies	21.54	1.079	19.53	1.047[#]	*	*	19.96	1.076	17.57	1.048	17.41	1.071	18.54	1.064
Mondial	17.85	1.064	15.66	1.058	17.91	1.065	11.80	1.044	16.54	1.046	16.42	1.066	15.96	1.058
Innovator	*	*	19.89	1.067[#]	*	*	*	*	*	*	*	*	*	*
Fianna	*	*	*	*	*	*	*	*	20.53	1.062	16.69	1.071	20.37	1.066
F12108	*	*	*	*	21.37	1.090	*	*	*	*	*	*	*	*
Laperla	*	*	*	*	13.66	1.058	*	*	*	*	*	*	*	*
Almera	*	*	*	*	*	*	12.95	1.051	*	1.043	*	1.057	*	1.050
Crop 34	*	*	*	*	*	*	17.20	1.074	*	*	*	*	*	*
Rumba	*	*	*	*	*	*	17.95	1.075	14.58	1.034	*	*	*	*

DM – Dry Matter; SG – Specific Gravity; W-C- warm to cold growth period; C-W- cold to warm growth period

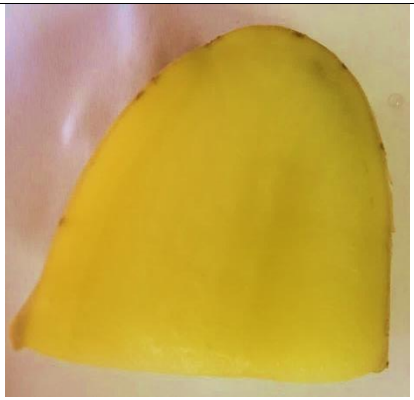
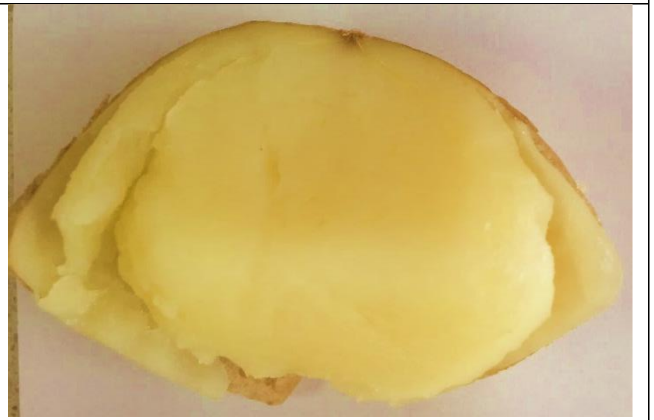
6.5 Conclusions and recommendations

The images of all the different cultivars over the seven different regions (Tom Burke, Bultfontein, Douglas, Pietersburg, Middelburg, Aurora and Ceres) on which DM analysis was conducted were used to make the final evaluation (Table 6-3). From the images it became clear that with cooking different cultivars form cracks in the flesh at different places. From this it was concluded that the cooking test can categorise different potato textures into four classes. It was found that DM analysis shows agreement with the images. Higher DM cultivars tended to have more cracks while low DM potatoes had few little to no cracks.

The baking test, as well as the fork test, were found to be unreliable methods of textural classification. It can, therefore, be concluded that the proposed boiling test together with the visual guide can be used to visually classify potatoes based on their textural properties. Four categories are proposed to classify potatoes using the boiling method. The categories are based on the manner in which tubers crack when boiled.

It is suggested that this method be tested together with relevant individuals involved in the potato industry such as farm level workers, pack house and sorting workers, farmers and the processing industry. This will ensure that if any problems are experienced by the individuals they can be resolved prior to the launch of the method.

Table 6-3: Classification of different cultivars based on visual appearance after being subjected to a pre-determined cooking test.

Group	Group1	Group 2	Group 3	Group 4
Category	Waxy	Waxy/Floury	Floury	Processing
			 	
Cracks	No cracks	1 Crack	2-3 Cracks – pulling away from sides with cracks	Pulling away from sides without cracking. Disintegration of the flesh

6.6 References

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Chapter 7: Conclusion and recommendations

"A commitment: The will to act and to keep on acting until the job is done." – Unknown

7.1 Introduction

Food based dietary guidelines (FBDG) form the basis of national eating patterns and lead the way for nutrition, health, agricultural policies and education programmes by providing guidelines to achieve healthy eating habits in line with national food preferences (FAO, 2020). One of the 11 South African FBDG advises consumers to "make starchy foods part of most meals". This guideline encourages the consumption of "*sufficient dietary carbohydrates from minimally processed, traditional and indigenous foods that are rich in starch*" (Steyn, et al., 2008). In South Africa, the starch portion of meals is usually dominated by maize meal. The average household food expenditure on maize meal is 23% in comparison to 7% of total food expenditure spent on potatoes (Vermeulen & Schönfeldt, 2020). Furthermore, in a country where dietary choice is guided by price, potatoes provide the most nutrients per monetary value, as well as yielding more edible food, in less time, on fewer hectares than any other major staple crop with no processing, other than cooking, required (Devaux, et al., 2014).

In a recent South African study, models were developed to measure the cost and affordability of healthy eating at a national level. These models take demographics, price and consumption patterns into account to recommend a food basket that fulfils the needs of a healthy diet. It is noteworthy that potatoes are listed as a staple food and included in the "Nutritional balanced food basket", the "Moderate-cost food basket", as well as the more economical "Thrifty healthy food basket" (Vermeulen & Schönfeldt, 2020).

Potatoes are a sparsely traded commodity due to their bulkiness and limited post-harvest storability. Therefore, potatoes are less susceptible to price volatility at a global level. However, local agricultural practices and sporadic weather phenomena, such as droughts, can affect potato prices within a country. Potatoes are a good choice to include in a thrifty healthy food basket due to its relative price stability (Svubure, et al., 2016).

The highly debated EAT-Lancet report, published in January 2019, promotes the inclusion of potatoes in the diet. This report encourages the consumption of diets high in plant-based foods and recommends the consumption of 50g or 164kJ of potatoes each day. As the consumption of potatoes and more specifically, the promotion of potatoes as a nutrient dense crop are discussed in highly accredited research reports, the role of this crop within country specific diets warrants further investigation. This report focuses on the production and consumption of foods in an environmentally sustainable manner (EAT-Lancet , 2019).

It became evident how important country specific actions, which also take into account consumer preferences and production needs, are when seeking a global solution for sustainable production. There is a need to understand the delicate and intricate links between sustainability and nutritional considerations from a consumer perspective. Through understanding and influencing the end user (consumer), information can be used up-stream to inform policies in such a manner that all the participants who are involved are satisfied and cooperatively strive to achieve the targets as set out in the SDGs.

Sustainable food choices are a fairly new concept for many South African consumers. The golden thread that is currently woven into most narratives, is the importance of sustainable actions for a prosperous future. This thesis provides evidence on how potatoes can fulfil the role of a high quality sustainable nutrient dense staple food.

The overarching goal of the study was to explore the sustainability of potatoes in the South African market focusing on the entire value chain from farm to fork. Included is the description of internal quality considerations as the foundation of the classification system, taking into account the various growing regions and production practices in the country. By considering current and emerging global research agendas, additional outcomes and aims were identified that were relevant to the project.

7.2 Overview of the study

Since the Neolithic age, technology and human development have led to increased production of agricultural crops. At the turn of the 18th century, mechanisation and yield outcomes increased resulting in increased carbon emission associated with food production. This placed the agricultural sector under the spotlight in the context of sustainability discussions, together with the nutritional value of food. Therefore, increasing the nutritional value of food and reducing carbon emissions became the two of the main concerns of agricultural food production (Taiz, 2013). This state of affairs challenged the agricultural and health sectors to become more involved in the shaping of the definition of sustainable food systems and healthy, sustainable food baskets. Therefore, in future, food-related policies should support a sustainable food system.

Developing sustainable diets requires the inclusion of the three main components or pillars of sustainability namely; the social, economic and environmental components. The social (people) component of sustainable food systems takes the human aspect into account. This ensures food security through the production of enough food in a manner that guarantees access to food for all in an ethical way. The economic (profit) aspect looks at the financial viability of production from farm to fork, supporting the longevity of business and improving return on investment. The environmental pillar considers efficient use of resources and methodologies that minimises losses and waste. The end goal of sustainable diets is to provide a growing population with nutritious food that is produced in such a manner as to avoid excessive use of resources that leads to the degradation of natural resources (Smetana, et al., 2019). Country specific food guides can assist in the development of such food systems and can act as a point of departure for additional research topics.

Nutrient sensitive sustainable agricultural production for food security and nutrition is an area of both concern and opportunity. Embracing this research opportunity can alleviate concerns and pave the way for future planning. This thesis has endeavoured to embrace the opportunity that this provides within a scientific domain, to investigate a few critical aspects in the South African staple food realm with a more specific focus on potatoes and sustainability. This thesis had five main objectives which were reported in separate chapters.

Chapter 1 served as an introductory chapter setting the stage and providing background information to support the subject matter of the study as a whole. **Chapter 2** reports the investigation which set out to determine a sustainability index for the South African potato sector. This index shows the potential sustainability outcome of potatoes compared to other staple foods. This sustainability index, which plotted greenhouse gas emissions and water use efficiency of different staple products against the nutrient density of the products can be used to identify foods that provide maximum nutritional outputs and resource use efficiency in association with minimal greenhouse gas emission. Sustainable agricultural systems are the way of the future. To ensure that the South African potato sector is on par with global scalable planetary guidelines, quantifiable research is required that provides reliable results. The data generated in this thesis show potatoes' water use efficiency, high nutrient density and low greenhouse gas emissions, compared to other commonly produced staple crops. According to the sustainability index which was used, potatoes are classified as a sustainable nutritious food source that can contribute to feeding humanity in the future in a sustainable manner. These are reassuring results for the growing potato consuming South African market which is expected to increase by 1.2% per annum over the next 10 years. This predicted growth is fuelled by increased class mobility and modest economic and income growth (Vermeulen & Schönfeldt, 2020). These findings can guide the sector to align itself with current developing legislation on sustainable production and improve food and nutrition security within the South Africa context.

Unfortunately, agricultural systems have never been explicitly designed to promote human health and, instead, mostly focused on increased profitability for farmers and agricultural industries. To maintain healthy populations, it is important to focus on the quality of the food (and nutrients) produced, rather than simply the amounts (kiloJoules) produced. Determining the quality of nutrients is possible through detailed chemical analysis and allows for informed decision making when creating dietary guidelines. Having accurate, as well as practical analytical methods available to role-players within the field of food and nutrition ensures that reliable results are obtained.

Exploring the protein quality of potatoes is new and has not been done previously in South Africa. Often the protein in plant foods is overestimated when using nitrogen to protein conversion factors (Mariotti, et al., 2008), however, this study **(Chapter 3)** found that the Jones factor of 6.25 delivers reliable results for potatoes. Results on the protein quality of potatoes showed that even though potatoes do not contain high amounts of protein (1.8g/100g), they do contain protein of a high quality.

External factors can have an effect on the nutritional, as well as textural properties of potatoes. The heterogeneous South African agricultural landscape varies from sub-tropical humid areas to dry desert-like areas. This diversity allows for year round production of commodities in the different agricultural regions of the country. However, the variance in environmental conditions, together with their associated area specific agricultural practices, lead to differences in the internal characteristics of potatoes. Current classification methods, as observed at retail level on product packaging is based on cultivar specific characteristics. However, a study of the literature and results as presented in this thesis found that external factors have a greater effect on the internal textural properties than specific cultivar attributes. To understand the effect that specific environments and cultivars have on one another, as well as the effect on the internal attributes of potatoes, the following research was conducted. Potatoes from seven cultivars and 10 regions were systematically collected as part of the Potatoes South Africa workgroup project over a period of three years resulting in extensive data sets for each region.

This study **(Chapter 4)** found that certain cultivars reacted more to external conditions than other cultivars by exhibiting greater variance in textural properties over different regions for the same cultivar. Furthermore, external variables, as observed in different production regions, have varying effects on the internal textural properties of potatoes. The textural properties of a potato are formed by a collection of variables, thus complicating the exact outcomes that a combination of external variables will have on the internal characteristics of the tubers. However, there are certain variables, such as heat units and water application that affect quality parameters to a greater extent than other variables. Certain cultivars (Lanorma, Valor and Sifra), are less influenced by fluctuating agricultural and environmental conditions and thus delivers tubers of a more consistent quality irrespective of external factors.

Worldwide there are approximately 5 000 different potato cultivars, with cross-breeding for improved yield and specific characteristics occurring at an increasing rate causing continuous species growth. The textural diversity found within the *Solanum tuberosum L.* species is one of the main drivers behind its popularity as a multifaceted food in the various sectors of the food industry from fresh to processed. Ensuring that specifically cultivated tubers are fit for their intended purpose, systems or groupings are desirable to make is easier for the end user to identify predetermined textural characteristics. The different potato consuming sectors use a variety of physical and biological analyses to determine textural characteristics. The most common methods were identified and explored to determine their reliability. From this study it was found that dry matter, specific gravity and starch can be used to classify potatoes into textural classes. Dry matter content proved to be the most robust method to use in classification of internal textural properties **(Chapter 5)**. However, this method cannot be readily applied, except in highly sophisticated environments.

Because of the fast moving pace of harvesting and packaging to ensure tubers reach the market as soon as possible, classification methods were evaluated to identify the best methods available to the market to classify potatoes for end use. The South African potato crop is used by four main markets, namely for processing (22%), domestic use (39%), the informal fresh market (32%) and the seed market (7%) (BFAP, 2019).

Tubers that are earmarked for the processing industry undergo rigorous testing and evaluation to ensure compliance with specific standards required for high turnover production. This ensures minimal product loss during production. The processing industry uses high tech, high cost and fast turnover methods to test the textural properties of potatoes. The most common method used by processors to evaluate processing quality is to determine the dry matter content of the batch. Specific gravity is one of the arguably simpler to perform methods used by small scale producers to classify potatoes, because it requires less equipment and specialised skills. Therefore, a need was identified by industry for the development of a reliable method to classify potatoes at farm level. Subsequently, a boiling method was developed that can be used at farm or retail level for classification purposes of potatoes. In this chapter the results show that tubers exposed to this method could be classified based on cracks that appear in the flesh of the tuber after following a standardised cooking procedure. No cracks are an indication of a waxy tuber, while an increase in cracks rendering a tuber either waxy/floury (1 crack), floury (2-3 cracks) or processing (disintegration of the flesh) **(Chapter 6)**.

Robust scientific data to support potatoes as a staple food has great potential from an economic, social and environmental perspective. It was and is important to explore the role that potatoes play in the South African agricultural landscape to gain insight into this diverse food crop.

7.3 Limitations of the study

It is known that the conditions under which tubers are cultivated have an effect on the internal quality of the tuber. Modern farming practices and changing geographical weather patterns necessitate changes towards more irrigation-based production. In South Africa potato production occurs mostly under irrigation, with the exception of specific localities such as certain locations in the Eastern Free State. Due to the limited number of dry land harvests the real effect of dry land vs irrigation was not explored in this study. However, a study conducted in 2013 found that tubers planted under irrigation produced potatoes that were more cultivar specific with associated sensory attributes of each cultivar while tubers planted under dry land conditions were more similar to one another in terms of textural characteristics (Booysen, et al., 2013).

Monetary and environmental costs of potatoes were not included in the sustainability index due to model limitations and scope.

7.4 Conclusions and recommendations

During this study the role of potatoes in South Africa in a sustainable food system was explored. There is strong evidence demonstrating that food production plays a significant role in environmental degradation and increased greenhouse gas levels. Considering the environmental impact of agriculture, a need was identified to quantitatively express the relationship between the environmental impact versus the nutrient density of specific foods. It was found that tubers can play a significant role in achieving sustainable outcomes in terms of decreased greenhouse gas emissions (GHGE), as well as increased water use efficiency. Furthermore, this information can be used in discussions on environmental and economic outcomes and used to successfully communicate this information to the relevant audience.

Even though potatoes do not contain high amounts of protein, they do contain high quality protein and can contribute to total protein consumption. This is a novel finding in the South African domain and can be used to form part of consumer education campaigns and dietary guidelines.

Changing environmental factors have a significant effect on the agricultural landscape which is further influenced by geographical variance within South Africa. Changes in external conditions are continuous and as seen in this study, can have a significant effect on the internal characteristics of potatoes. Results from this study can be used to make future predictions relating to crop outcomes.

It is recommended that the study be repeated in the various experimental plots over time to improve the robustness of the data and improve the prediction tool.

The consistent occurrence of variation in textural characteristics necessitates scientific, as well as practical ways to classify potatoes in a local context, that is applicable to local agriculture and consumer outcomes. Data showed that dry matter is the most robust method to classify potatoes in a laboratory environment. However, this is not possible in a fast paced working farm or retail environment. The newly developed farm level boiling test for classification purposes addresses this dilemma. Industry, at farm and retail level, has shown interest in the boiling method for classification which will be further tested prior to being implemented.

7.5 Lessons learned

Certain challenges were faced in this study that sometimes caused frustration while also providing unique learning opportunities. On several occasions, samples that were earmarked for analyses were lost. On one occasion samples went missing while being transported by a courier company from the farm to the laboratory. On another occasion, samples were stolen at the laboratory prior to being analysed. This had both financial and time implications for the study as new samples had to be sourced either from the same harvest or from a later harvest. This also draws attention to the ongoing food security struggle faced by many South Africans, who resort to stealing to feed their families. This hurdle was overcome by placing bio-hazard “not safe for human consumption stickers” on the tubers during transportation.

Challenges of a biological nature were also experienced during this study. On closer inspection, some tubers that seemed perfect at harvest were found to contain worms (*Haemonchus contortus*) or in one case, the tubers were infected with severe hollow heart. In order to preserve the reliability and integrity of the study it was decided not to use such tubers as it was felt that they could produce unreliable results and skew data.

7.6 Final thoughts

During the four years of this study, tubers were sourced from all over South Africa and transported to Pretoria where they were analysed. The candidate was physically involved in the planting and harvesting of ten crops, gaining insight into the labour that this high input crop necessitates. It is estimated that 3 242 tubers were used in this study from 44 different cultivars from 24 different farms. Apart from the most commonly consumed well known tubers that are discussed in detail in this study, new cultivars, such as Magenta Love, a new pink potato, and processing tubers, F12108 and Crop34, with their high dry matter content, were analysed. Each new cultivar and region of harvest provided a new learning experience that required flexibility in the modus operandi that was followed. Tubers from regions where the soil contains more clay necessitated a lot more effort to remove mud adhering to the tubers, while tubers that came from the Sandveld barely had any traces of sand on them.

This study proved that tubers can form part of a balanced, sustainable diet which can contribute to global attainable guidelines. However, dietary changes and consumer preferences have made potatoes unpopular making them a food that is associated with high fat and high salt intake. This may be one of the greatest challenges that the South African and global potato sector face from a consumer and health perspective.

Global food production and consumption has reached a critical point. Changes in production associated with an increase in yield and quality can be noted as being one of the reasons behind a reduction in hunger rates, increased economic potential for people and decreasing early childhood mortality rates. However, the scale is starting to tilt as dietary choices are leading to an increase in obesity, overweight, heart disease and other non-communicable diet-related diseases in the midst of undernutrition, stunting and wasting (EAT-Lancet , 2019). Taking foods back to their original form, without the addition of salt, oil and processing and promoting them as such, can contribute to achieving the equilibrium where food and health complement each other on a global scale.

The call for action from all stakeholders throughout the food chain has been heard and should be adhered to by up- and down-stream players to ensure that the universal goal is achieved. Research on the topic acts as a first step in addressing this issue of food sustainability that has condemningly been labelled one of the greatest challenges of our time. The willingness and input from various sectors have proven that these challenges should be faced head on and all researchers should hold fast to the belief that food and nutrition will be triumphant in the end to reduce the occurrence of a variety of debilitating diseases and environmental outcomes.

7.7 Acknowledgements

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Appendix A – Ethical clearance

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

Date: 26 June 2017

ETHICS SUBMISSION: LETTER OF APPROVAL

Name of Applicant	Prof H Schönfeldt
Department	Animal and Wildlife Science Institute of Food, Nutrition and Well-being
Reference number	EC170501-123
Title	The development of a cost effective, high value methodology to differentiate between potato cooking types

Dear Prof Schönfeldt

The submission conforms to the requirements of the NAS EC. Any amendments must be submitted to the NAS EC on a relevant application form as used for the original application quoting the reference number and detailing the required amendment. An amendment would be for example differentiating within the research target population.

You are required to submit a progress report no later than two months after the anniversary of this application as indicated by the reference number. The progress report document is accessible of the NAS faculty's website: Research/Ethics Committee.

You are required to notify the NAS EC upon the completion or ending of the project using the form Project Completed. Completion will be when the data has been analysed and documented in a postgraduate student's thesis or dissertation, or in a paper or a report for publication.

The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

The NAS EC wishes you well with your research project.

Yours sincerely,

Chairperson
NAS Ethics Committee