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Genetic gain on grain yield, agronomic traits and malting quality of selected barley cultivars in the Western Cape Province, South Africa

by

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DECLARATION

I, Qiniso Kennwell Ndlovu, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

This study evaluates the genetic gain in nine barley cultivars released from 2004 to 2020, focusing on agronomic and malting quality traits. Field experiments were conducted in two locations during the 2023 growing season, Caledon and Heidelberg, representing different rainfall conditions. Caledon, a high rainfall area, had the highest grain yield, with Malgas (S20) emerging as the top performer with a yield of 6.17 t ha^{-1} and 4.50 t ha^{-1} in Heidelberg a low rainfall area. Genetic improvements in ear m^{-2} were observed in Bitou (S19), which produced 516 ears m^{-2} despite a lower plant density of 8 plants m^{-1} compared to older cultivars like Nemesia (S04), which produced 416 ears m^{-2} with a density of 9 plants m^{-1}. Recent cultivars bred at SABBI including Kadie (S16) and Malgas (S20) displayed shorter plant heights at 63 cm compared to older cultivars, Disa (S06) and Agulhas (S09) reaching heights of 73 cm and 75 cm, indicating the incorporation of dwarfism trait. Contrasting trends in total nitrogen content were observed between the locations, with Caledon showing a positive relationship with years of release ($y = 0.0088x - 16.167$), while Heidelberg exhibited a negative relationship ($y = -0.0045x + 10.872$). Plumpness consistently improved over time, with Bitou (S19) showing the highest plumpness in both locations (Caledon: 95.82%, Heidelberg: 96.97%). However, significant differences and negative relationships were observed in screenings in both locations (Caledon: $y = -0.192x + 390.1$, $p<0.045$; Heidelberg: $y = -0.0594x + 120.62$, $p<0.041$). This study highlights the importance of barley breeding and genetic gain on grain yield and malting quality. Continued breeding efforts are crucial for enhancing barley production in diverse climatic conditions.

Key words: Malting barley, genetic gain, grain yield, malting quality

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DEDICATION

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CV	Coefficient of variance.
cm	Centimetre.
DAFF	Department of Agriculture, Forestry and Fishery.
g	Gram.
ha	Hectare.
ha^{-1}	Per hectare.
kg	Kilogram.
m	Meter.
m^2	Square metre.
m^{-2}	Per square metre
ml	Millilitre
SABBI	South African Barley Breeding Institute
%	Percentage

CHAPTER ONE

BACKGROUND AND INTRODUCTION

1.1 Introduction

Barley is a cereal crop belonging to the genus *Hordeum*, within the tribe *Triciceae* (syn. *Hordeae*, *Hordeeae*), in the family Poaceae (Giraldo *et al*., 2019; Sato, 2020). Other species belonging to the family Poaceae include wheat (*Triticum* spp.) and Rye (*Secale cereale* L.), most characterised by their inflorescence, which is a spike instead of the panicle that occurs in most other grasses (Blattner, 2018). Ourari *et al*. (2011) classified the genus *Hordeum* into 32 species and 42 taxa including diploid (2*n*=2*x*=14), tetraploid (2*n*= 4*x*=28) and hexaploid (2*n*=6*x*=42) cytotypes. The study by Blattner (2018) suggested that the species wild barley (*Hordeum vulgare* subsp. *Pontaneum*), bulbous barley (*Hordeum bulbosum*) and wall barley (*Hordeum murinum*) belong to subgenus *Hordeum*, and all other species belong to subgenus *Hordeastrum*. *Hordeum bulbosum* is a perennial outcrossing species found in the Mediterranean region and there are two cytotypes within this species including diploid (2*n*=2*x*=14) and tetraploid (2*n*=4*x*=28) (Devaux, 2003). Wall barley (*Hordeum murinum*) is an annual native grass that mostly self-pollinates (El-Shatnawi *et al*., 1999). It is recognised as three subspecies with different ploidy levels: *subsp. glaucum* (Steudel) Tzvelev (2*n*=2*x*=14), *subsp. murinums. str*. (2*n*=4*x*=28) and *subsp. leporinum* (Link.) Arcangeli (2*n*=4*x*=28, 2*n*=6*x*=42) (Ourari *et al*., 2011).

Bizuneh and Abebe (2019) stated that cultivated barley is normally divided into three subgroups; six-row (*Hordeum vulgare*), two-row (*Hordeum distichon*) and the seldom cultivated intermediate (*Hordeum irregulare*). Cultivated barley types are mostly diploids, but tetraploids and hexaploids are also used (Kumar *et al*., 2012). Both cultivated two-row and six-row barley types and their wild species *Hordeum spontaneum* are diploid species (Blattner, 2018). Kumar *et al*. (2012) classified two-row barley with shattering spikes as *Hordeum spontaneum*, while two-row barley with non-shattering spikes was classified as *Hordeum distichum*. The two lateral spikelets of two-row barley are smaller with reduced stamens and a rudimentary ovary and stigma (Tehulie and Eskazia, 2021). This type of barley has central florets that produce kernels and lateral florets that are sterile (Blattner, 2018). Six-row type barley has a spike notched on opposite sides with three spikelets on each notch (Tehulie and Eskazia, 2021) containing a small individual flower, or floret, which develops a kernel (Blattner, 2018).

Barley is a versatile crop and its primary economic use differs for each country (Dubey *et al*., 2018). The use of barley generally depending on cultivar type of hulled and hulless (naked) barley (Tricase *et al*., 2018). The hulled type has a fibrous husk while the hulless barley is sometimes defined by the existence of a thin hull tightly adhering to the grain perisperm (Baidoo *et al*., 2019). It has been suggested that about 70% of barley crop produced in the world has been used for animal feed (Sakellariou and Mykona, 2020). The large use of barley in feed industry is due to advantage of its adaptability to different climatic conditions (cold and drought) and poor soil quality, making it available where other cereals are not (Badea and Wijekoon, 2021). According to Tricase *et al*. (2018) the main products utilized in barley animal feed are processed barley grain, plant forage, malt-based alcoholic beverage by-products and milling. There is no specific quality restriction to use barley grain in animal feed industry (Bleidere and Zinta, 2012). Sakellariou and Mykona (2020) state that 21% of the world production is used in distilling and malting industries. Barley is used to make most beers because its carbohydrates are particularly well suited for malting (Bleidere and Zinta, 2012). Barley can also be used to make whiskey, quite popular in Ireland and Scotland (Badea and Wijekoon, 2021). It is suggested that 6% of the world production has been mainly used for human consumption (Sakellariou and Mykona, 2020). In the food industry, naked barley is considered more valuable as the absence of the hull increases the content of starch, protein, and β-glucan in barley grains (Geng *et al.*, 2022). Barley starch plays an important role in the food industry , where it is used as sweetener and binder (Tricase *et al.*, 2018). Barley is becoming less desirable for food because of the difficulty of its husk removal and absence of gluten protein content (Baidoo *et al.*, 2019). Although it is still a staple food for humans in some countries that includes Tibet and China (Geng *et al.*, 2022). In the interest of renewable anergy, the remaining 3% has been used for the production of biofuel (Tricase *et al.*, 2018).

1.2 Motivation of the research

Barley (*Hordeum vulgare* L.) production has been successfully increasing over the past decades, largely due to improvements in breeding programmes across the world (Abeledo *et al.*, 2003; Rodrigues *et al.*, 2020). These breeding programmes have been mainly focused on the improvement of agronomic traits such as grain yield, disease, lodging resistance and malting quality trait for brewing purposes (Martin *et al.*, 2018; Giraldo *et al.*, 2019; Mourad *et al.*, 2019). Genetic gain has been widely used in plant breeding to evaluate the success of the programme, and helps in improving breeding strategies (Gupta, 1998). However, there are no reports on genetic gains of agronomic and malting quality traits in the South African barley breeding programme. Therefore, there is a need to study the genetic gain of this breeding programme in terms of grain yield and malting quality over the past decades under the dry land conditions in the Western Cape. The information generated from the study will assist breeders to improve breeding strategies to meet the increasing demand for the malting barley industry.

1.3 Research questions

Research work on assessing the genetic gain of agronomic and malting quality traits of the nine accessions of registered barley cultivars bred within South African Barley Breeding Institute (SABBI) is based on the following research questions:

- What is the status of the yield potential of nine barley cultivars bred at SABBI?
- What is the status of nine barley cultivars bred at SABBI in terms of agronomic characteristics?
- What is the effect of cultivars on malting quality traits of the nine accessions of registered barley cultivars bred at SABBI?

1.4 Objectives of the research

The main objective of this research work was to investigate the genetic gain agronomic and malting quality traits from nine accessions of registered barley cultivars grown in South Africa. The specific objectives are:

- To establish progress on genetic gain of grain yield on nine barley cultivars
- To establish progress on genetic gain on nine cultivars for agronomic characteristics
- To establish progress on genetic gain for malting quality traits among nine accessions of registered cultivars bred at SABBI.

1.5 Delineation of the research

A study of barley cultivars developed and produced under dryland conditions in the Southern Cape (Caledon and Heidelberg) of the Western Cape Province in South Africa.

1.6 Chapter Outline

This dissertation consists of six chapters. Chapter 1 provides the background and introduction to the study. Chapter 2 presents the general literature review of the study. Chapter 3 is the general materials and methods used. This is followed by chapter 4 which gives results and Chapter 5 discussions. Chapter 6 provides the conclusions and recommendations from the study.

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CHAPTER TWO

GENERAL LITERATURE REVIEW

2.1 General Introduction

Worldwide, barley is the fourth most important cereal crop after wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*) (Dubey *et al*., 2018). It is adapted to wide environmental conditions and grows in many areas unsuitable for other cereal crops (Waluchio *et al*., 2015). Barley has been grown globally for more than 10 000 years (Mohammadi *et al*., 2020). The world annual production of barley is estimated to be more than 140 million tons acquired from nearly 50 million hectares (Tricase *et al*., 2018). Tehulie and Eskazia (2021) ranked the five leading barley producing countries in the world as Canada, Ukraine, Turkey, Australia and Russian Federation. Due to numerous factors that include agricultural practices, climate conditions, soil characteristics and the cultivar cultivated, barley yield changes every year (Sato, 2020).

During an interview conducted on 1 March 2022, Tobie van Rensburg (Model Farm Commercial Manager at Anheuser Busch Inbev SA/NV stated that South Africa's dryland production in 2020 was estimated to be 353 627 tons acquired in 131 836 hectares of land (2.68 t/Ha), while under irrigation there was an estimation of 55 169 tons acquired from 9 700 hectares (5.69 t/Ha). The production differed in 2021 due to number of factors that includes soil condition, climate condition and agronomic practises. Under dryland, 275 000 tons were produced from 82 937 hectares (5.32 t/Ha), while under irrigation there was an estimation of 61 443 tons from 9 000 hectares (6.83 t/Ha).

Kifle (2016) and Ahmed (2021) ranked the major barley producing countries in Africa as Morocco (2.1 million tons), Ethiopia (1.7 million tons), Algeria (1.3 million tons), Tunisia (0.9

million tons) and South Africa (0.307 million tons). South African barley is mainly produced in the Western Cape under dryland conditions, Northern Cape under irrigation, as well as Limpopo and it is also grown by some small-scale farmers at Taung in the Northwest (Ajith *et al*., 2009; DAFF, 2019). Western Cape was the first province to produce barley, and, as the demand of this crop increased over the years, the production has been expanded to Northern Cape Province under irrigation (van Rensburg 2022, personal communication). The Western Cape Province is the largest producer of barley in South Africa with a contribution of 85%, followed by the Northern Cape and Limpopo Province with contributions of 10% and 3%, while smaller quantities of barley with a share of 2% is found in the Northwest province (Khumalo, 2019; DAFF, 2019). The demand for barley in the brewing industry is constantly increasing, which affects its market price for the countries that import the crop for brewing purposes (Daničić *et al*., 2019). In South Africa, the South African Breweries (SAB) is the major buyer for malting barley (van Rensburg 2022, personal communication).

Barley producers in South Africa have a guaranteed market for their produce as well as fixed price contracts with the buyers (Khumalo, 2019). Prior to 2011, the price of barley was fixed to a specific amount per ton. As more discussions were made by farmers about the contribution of barley to the economy of the country, the price of barley was determined using the criteria similar to the one used for wheat (van Rensburg 2022, personal communication). The lowest price for barley of R2009.1 per ton was experienced during the year 2010 while the highest was recorded in 2018 at about R3 427.01 per ton (DAFF, 2019). Moreover, it has been reported that the total annual production of this crop ranges from 250 000 to 300 000 tons per yearly depending on weather conditions and local consumption requirements for the product is around 306 610 tons per year (DAFF, 2019). To accommodate the demand of the breweries, barley is imported from France, United Kingdom, Ukraine, United State and Ethiopia in the form of malt or raw material (van Rensburg 2022, personal communication). The barley produced in

Southern Cape is malted at the Caledon malting plant which has an annual capacity of 180 000 tons per annum, while the barley from the Northwest, Limpopo and Northern Cape irrigation areas is malted at the Alrode malting plant which has an annual capacity of 42 000 tons per annum (SABBI, 2014).

2.2 Plant Breeding

Plant breeding is an art and science aimed at developing plant cultivars with high and stable yield potential (Acquaah, 2007; Osei *et al*., 2014; Caligari and Forster, 2015). However, this process is affected mostly by environmental and genetic factors (Fasuola and Fasuola, 2002). Similarly, like other breeding programmes, barley breeding programmes are generally aimed at improving the grain yield and quality traits (Bulman *et al*., 1993; Abeledo *et al*., 2003; Emebiri *et al*., 2009; Condón *et al*., 2009). Breeding of barley cultivars has been successfully achieved through intraspecific and interspecific hybridisation, although intergeneric hybridization has also been used to introduce novel traits of disease resistance genes into the existing cultivated cultivars (Rey *et al*., 2021).

2.2.1 Intraspecific hybridisation

The processes of domestication have resulted in radical narrowing of genetic variation of barley species. Constant breeding with uniformity has accelerated the process of domesticating barley and it has led to greater susceptibility of many crop diseases, pest and abiotic stress (Forster *et al*., 2000). Most of the commercial cultivars grown in South Africa such as ‘Erica,’ ‘Nemesia,’ ‘Agulhas,’ ‘Hessekwa’ and ‘Kadie’ were developed through deliberate intraspecific hybridization by the SABBI breeding programme. Amongst other cultivars, Hessekwa has been used intensively as a major gene donor for different traits including agronomic traits, malting quality, and disease resistance at SABBI breeding programme through intraspecific hybridisation. Hybridisation of two-row × two-row has been a successful tool to transfer desired quality traits, agronomic traits and disease resistance which include leaf blotch, leaf rust, sport form net blotch, powdery mildew, and net blotch (Xuel *et al.*, 1994; Schmierer *et al.*, 2004; Pierre *et al.*, 2010; Martin *et al.*, 2018). Martin *et al.* (2018) successfully transferred resistance genes of the net form of net blotch (which was observed in chromosome 6H) from the elite line to the commercial cultivar 'ERICA'. The intraspecific hybridisation with aim of improving yield and malting quality was also done by Schmierer *et al.* (2004) where they transferred quantitative trait loci (QTL) associated with the high yield from cultivar 'Baronesse' (a high yielding feed barley) to malting cultivar 'Harrington'. Goddard *et al.* (2019) revealed potentially novel loci associated with reduced physiological leaf spotting, powdery mildew and also favourable malt quality traits with a cross of cultivar Chevallier (two-row) and Tipple (two-row). Intraspecific hybridization has a potential benefit towards barley breeding programmes and this warrants further investigation to improving barley. Therefore, continued improvement of two-row barleys genes for agronomic, disease resistance and grain quality traits are needed.

2.2.2 Interspecific hybridisation

Barley is an inbreeding species and single plant selection which promotes uniformity (Forster *et al.*, 2000). Barley breeding through the interspecific hybridisation method is based on combinations of six-row × two-row winter barley and in most common cases, a cross between *Hordeum* species with different chromosomes (Subrahmanyam and Bothmer, 1987). The formation of haploid plants through chromosome elimination comes from a result of interspecific hybridisation, for example, *Hordeum* crosses with diploid and tetraploid *Hordeum bulbosum* (Subrahmanyam and Bothmer, 1987). A cross of six-row × two-row is done to introduce disease resistance traits, but this method requires many backcrosses to make the specific trait successfully merge. Six-row cultivars have contributed a leaf rust resistance trait to elite lines of two-row types in the SABBI breeding programme (de Klerk 2021, personal communication). The genetic yield potential of six-row barley can be increased by increasing its tillering capacity by crossing it with two-row type (Aikasalo, 1988). The inbreed lines derived from an experiment on ‘the effects of major genes on quantitatively varying characters in barley of six-row × two-row cross associated with V-v locus’, Powell *et al.* (1990) found significant differences between the double haploid and single seed descent population in terms grain yield from the whole plant, weight of straw from the whole plant and ear length. Historically for domesticated barley in the Fineland (Nordic country in Northern Europe), Aikasalo (1988) reported an increase of 10-15% in grain yield when genetical improvement was assessed in a period of a decade. This increase was found due to the interspecific hybridization of cultivar Olli (six-row) that had and acceptable malting quality and landraces of two-row barley. Unlike wheat, interspecific hybridisation of barley is not common because *Hordeum* consists of two quite distinct sections the grasses and the cereals. There are no recent reports on the interspecific hybridisation of barley.

2.2.3 Intergeneric hybridisation

The background of genetic arise from the transitions between wild genotypes to early domesticated germplasm, and from early domesticated germplasm to modern cultivars has left many potentially useful genes (Forster *et al*., 2000). Hybrids of cultivated barleys with *Hordeum* grass species are not likely to offer anything of practical worth as intergeneric hybridisation mostly failed to produce fertile plants from parental combinations. Such hybridisation creates genetic variability among the progeny which requires selection of combinations with desirable traits and further crossing to fix the selected genotype (Knežević *et al*., 2004). Efforts to improve the disease resistance of cultivated barley have concentrated more on intergeneric hybridisation of cultivated barley species like *Hordeum vulgare* crosses with wild barley species like *Hordeum vulgare* ssp. *Spontaneum*. (Zhang *et al*., 2001). Breeding programmes do not focus on population, but only aim to transfer particular attributes into cultivars from wild barley species (Ellis *et al*., 2000). Zhang successfully did intergeneric hybridisation *et al*. (2001), where they used it as an approach to transfer leaf rust *Puccinia triticina* and powdery mildew *Erysiphales* resistance loci from *Hordeum bulbosum* to *Hordeum vulgare*. Wild *Hordeum* species or other exotic germplasm may provide the source of genes needed to improve barley species have to go under a pre-breeding process because genetic variation could be too diverse to be used directly (Xu *et al*., 2017). The wild progenitor species and the primitive landraces of barley offer rich sources of genetic variation for crop improvement and these gene pools can be exploited using conventional crossing procedures, but with the aid of genetic maps, markers and quantitative trait locations (QTL analysis) greater precision can be obtained in selecting desired genotypes (Forster *et al*., 2000).

2.3 Breeding Methods

2.3.1 Molecular markers

Molecular assisted selection (MAS) refers to the use of DNA markers that are tightly linked to targeting loci to assist phenotypic screening (Salgotra *et al*., 2017). Plant breeding utilising the advances in DNA technology has attracted breeders and geneticists (Mourad *et al*., 2019). Markers can be used to confirm the identity of individual plant (Mandal *et al*., 2018). Molecular markers provide identification of genes’ response to winter hardiness, resistance to salinity stress and their chromosomal location in barley (Knežević *et al*., 2004). Molecular markers have been widely used in plant breeding for various purposes including analysing genetic diversity, tapping of the genes and marker assisted selection for different traits. Some of the successfully used molecular markers includes restriction fragment length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), simple sequence repeats (SSRs), single-nucleotide polymorphism (SNP) and diversity arrays technology (DArT) (Schmierer *et al*., 2004). These markers have widespread use in population genetic studies (Mandal *et al*., 2018). Forster *et al*. (2000) reported the genetic diversity of wild barley using molecular markers. A principal coordinate (PCO) plot of AFLP fingerprinting data of wild barleys from the Fertile Crescent showed that genotypes from Israel cluster separately from those of Turkey and Iran (Forster *et al*., 2000). There are also advantages as well as disadvantages associated with the use of markers (Mandal *et al*., 2018). The advantage of specifical "marker assisted back crossing" is that once started, it cannot be abandoned because polymorphism characterized for donor and recurrent parent is usually based on phenotypic differences. The disadvantage is that since marker polymorphism is to be established first, it will take a long time start actual marker-assisted back crossing (Farooq and Azam, 2002). Due to ongoing research taking place in the world, it is highly likely to see continued innovations in molecular marker technology to make it more precise, productive and cost-effective to investigate the biology of various traits of interest (Dizkirici *et al*., 2008; Owen *et al*., 2019). The DNA-based molecular markers have made the selection process easier by enabling early generation selection for key traits and thus, overcoming the drawbacks of conventional methods (Salgotra *et al*., 2017). At hand, plant breeders have an increasing collection of important plant gens at their disposal. It is advisable and important for plant breeders to continue collect more information on the gene functions and allelic variation. This information can be used to improve plant production by combining well characterised plant genotypes and fast selection of best progeny.

2.3.2 Genomic Selection

Along with advances in crop genome sequencing and the availability of genome-wide density marker systems, 'genomic selection' (GS) has emerged as a powerful selection tool in breeding programmes (Krishnappa *et al*., 2021). Voss-Fels *et al*. (2019) state that there are a number of studies that report the successful prediction of phenotypic performance using molecular markers for all major species of crops including maize, rice, wheat, sorghum, barley and cassava. Several key strategies have been used to employ MAS in crop improvement (Schmierer *et al*., 2004; Salgotra *et al*., 2017; Krishnappa *et al*., 2021). GS is a form of MAS with extended scope and advantages that simultaneously estimates all locus, haplotype, or marker effects across the entire genome to calculate genomic estimated breeding values (Salgotra *et al*., 2017). Application of GS in plant breeding programmes rely on a combination of different strategies such as pedigree information for higher prediction accuracies and obtaining breeding values of non-genotyped lines (Robertsen *et al*., 2019). Robertsen *et al*. (2019) stated that GS is a feasible option, whereby investments in genotyping could be recovered by making better selection decisions. GS results in equivalent or greater genetic gains over cycles of selection compared with traditional breeding strategies such as phenotypic selection (Tiede and Smith, 2018).

2.4 Genetic Gain In Plant Breeding

Genetic improvement (or breeding progress) has been described by the concept of genetic gain (Xu *et al*., 2017). Genetic gains or improvement is a science of selecting and producing genotypes possessing certain characteristics based on heredity of such characteristics (Condón *et al*., 2009; Booyse, 2014). Genetic gain is measured by the difference between a selected population and its offspring population (Xu *et al*., 2017). In terms of yield, genetic gain is the most important objective of plant breeding programmes (Rodrigues *et al*., 2020). The objective of all barley breeders in the world is to provide good genetic material that will perform consistently in a range of environmental conditions (Marshall and Ellis, 1998). It is important to understand changes produced by crop breeding on grain yield (Altaye *et al*., 2016). Trial methods as historical data and experimental designs such as randomized block design, complete randomized block design and Latin square design is used by breeders and agronomists to identify the yield potential of new genotypes (Marshall and Ellis, 1998). Plant breeders often evaluate their germplasm developed over time based on historical data or intentional experimental evaluation in order to assess genetic changes over time of their breeding programmes (Graybosch and Peterson, 2010; Rodrigues *et al*., 2020). The differences in breeding methods depend on the inbreeding of the population and the selection process. Plant breeders first predict the improvement in average genetic value of a population with each cycle of selection in a breeding programme before they begin to evaluate the genetic gain achieved over time (Tiede and Smith, 2018). The estimation of realised changes in genotypic values over multiple cycles or years is referred to as realised genetic gain (Xu *et al*., 2017).

The evaluation of genetic gain can be done by use of various methods (Booyse, 2014). The first approach is to estimate genetic gains over time by comparing yield of long-term checks with new experimental lines (Graybosch and Peterson, 2010). Robust experimental designs including old cultivars and newly developed cultivars is used to check if the new cultivars indeed outperform old cultivars (Ortiz *et al*., 2002; Emebiri *et al*., 2009; Rodrigues *et al*., 2020). The second approach is based on a long-time series of yield data mostly coming from long-term experiments compared to a historic check cultivar (Booyse, 2014; Rodrigues *et al*., 2020). Several studies on genetic gain of malting quality traits including extract content, friability, viscosity and malt extract have been reported based on the use of historical data approach (Knežević *et al*., 2004; Emebiri *et al*., 2009; Condón *et al*., 2009; Laidig *et al*., 2017). Many statistical methods have been proposed for the use of genetic assessment. The most widely used method is linear regression described by Trethowan *et al*. (2002) and quadratic regression methods implemented by Rodrigues *et al*. (2020). To evaluate the relationship between variables and account for the degree of freedom, most studies use linear regression analysis to estimate and determine the rate of genetic gain (Ortiz *et al*. 2002, Abeledo *et al*., 2003; Condón *et al*., 2009; Rodrigues *et al*., 2020). The other method is Analysis of Variance (ANOVA) which optimise the blocks, localities, years and genotypes in determining variance (Graybosch and Peterson, 2010).

Factors affecting genetic gain in barley includes agronomic practices and environmental factors (Bulman *et al*., 1993; Abeledo *et al*., 2003). Genetic gain in barley is influenced by both agronomic practices and environmental factors (Bulman *et al*., 1993; Abeledo *et al*., 2003). However, evaluating genetic gain presents challenges, especially when comparing older and newer cultivars (Singer *et al*., 2021). The viability and quantity of older cultivars are poor to those of newer ones due to the inherent lifespan of seeds. The genetic makeup of seeds, including their chemical composition and the genes that determine their longevity, plays a crucial role in their storage potential (Ramtekey *et al*., 2022). To utilize older cultivars effectively, it is necessary to multiply them to enhance both their quantity and viability, as seeds require a moisture content of at least 12% for successful germination (Sato *et al*., 2016). Proper storage of barley is vital for maintaining its ability to germinate quickly, which in turn helps preserve its quality (Abushu and Kefale, 2018). Barley grains should be stored in conditions that promote rapid and uniform germination while protecting them from excessive moisture and pests (Abushu and Kefale, 2018). Greater seed longevity increases the likelihood of meeting regulatory standards for desirable germination rates, thus contributing to overall crop production and enhancing economic value within agricultural systems (Ramtekey *et al*., 2022). Additionally, climate change may affect comparisons of genetic improvements, as older cultivars may not adapt as well to current environmental conditions, potentially leading to suboptimal plant growth and increased susceptibility to biotic and abiotic stresses (Singer *et al*., 2021). Finally, the availability and integrity of historical data pose challenges in comparing old and new cultivars, as data collection methods can vary significantly over decades (Elshafei *et al*., 2024). Newly developed cultivars have more potential to have improved agronomic characteristic than the old cultivars (Rodrigues *et al*., 2020**)**. The realistic utilisation of genetic resources in agriculture has not only brought about changes in the crop yield and quality, but also opened up newer and unexpected potential perspective including improvement of novel traits (Hoisington *et al*., 1999).

2.5 Genetic Gain In Barley Breeding Programme

Genetic gains in barley have been reported from several studies (Abeledo *et al*., 2003; Condón *et al*., 2009; Altaye *et al*., 2016; Rodrigues *et al*., 2020). Abeledo *et al*. (2003) stated that the main component affecting grain yield in barley was the number of grains per unit area, associated with the number of spikes and total biomass. Similarly, Bulman *et al*. (1993) stated that yield improvement observed over time was associated with the increases in the total above-ground biomass. Yield increases that has been achieved by farmers resulted from the impact of both genetic and crop management practices (Abeledo *et al*., 2003). It is expected that genetic improvement will keep increasing yield potential at least as efficiently as it has increased during the last decades (Rodrigues *et al*., 2020). Ortiz *et al*. (2002) state that genetic gains through plant breeding within a specific period show the benefit of breeding efforts and also provide understanding about the phenotypic changes that are associated with this improvement. It is important to have a better understanding of the genetic architecture of traits and utilisation of modern breeding strategies for the improvement of genetic gain to meet the demand for agricultural products (Xu *et al*., 2017).

In a study that was conducted by Abeledo *et al*. (2003), they concluded that barley breeding has increased grain yield through increases in total biomass and in grain number per square metre. Similar results were observed by Rodrigues *et al*. (2020) where grain yield improvement was successfully observed through increases in the harvest index and number of grains per square metre, attributed to the genetic improvement of tillers which resulted in higher number of spikes per square metre and the reduction of plant height in the modern cultivars. Assessing genetic improvement impact on physiological traits determining barley yield may help to identify characteristics of either limited or potential value for future breeding (Abeledo *et al*., 2003). The efficiency of past improvement work on the advances in genetic grain yield potential needs to be measured over time (Altaye *et al*., 2016). According to Ortiz *et al*. (2002), evaluation of genetic yield improvement from long term yield trials may be biased because it is difficult to determine the influence of cultivation techniques on yield throughout the testing period. The breeding approaches that allow rapid changes in the factors contributing to genetic gain are needed to obtain higher genetic gains in breeding programmes (Krishnappa *et al*., 2021).

Emebiri *et al*. (2009) demonstrated that major genetic gain in terms of foliar disease resistance, acceptable malting quality, boron tolerance, cereal cyst nematode (CCN) and good grain plumpness can be improved by the combination of two-row Harrington and six-row Morex cultivars. Their micro-malting quality results of derived lines showed an impressive quality improvement compared with the recurrent parents. Malt extract levels were increased by 1.5 to 2.0%. Condón, (2006) recorded an increase in malt extract percentage of 0.1% per year, which resulted in an overall increase of 4% during the 40-year period in Minnesota. Emebiri *et al*. (2009) also recorded quality improvement increases in ß-glucanase levels from 375 to between 447 and 512 units and reductions in wort ß-glucan levels by 30–60%. The malting and brewing industries quality requirements are specific and their reluctance to adopt new cultivars has led to a situation where relatively few cultivars dominate for long periods of time (Condón, 2006). Breeders' major goal is to create malting barley for brewing with maximum extract yield, sufficient nutrient for yeast growth, fermentable sugars for alcohol production and balanced combination of high molecular weight compounds to contribute to mouth feel and foam and flavour quality (Knežević *et al*., 2004).

Barley genetic gain report studies normally focus on specific geographic regions and span from a decade up to 108 years (Ortiz *et al*., 2002; Abeledo *et al*., 2003; Condón, 2006). The number of cultivars evaluated in these reports include as few as 9 cultivars and as many as 90 cultivars. The use of an elite line by introducing it to commercial cultivars is common in the assessment of genetic gain (Ortiz *et al*., 2002; Emebiri *et al*., 2009). Rodrigues *et al*. (2020) chose four cultivars to represent each decade based on the significant participation in the barley cropped area. General conclusions from these studies can be made about the productivity and economic impact of plant breeding for a region. However, little can be shared about genetic gains within breeding programmes, since a small sample of genotypes from each program is used. Genetic gain studies within single plant breeding programmes can be used to assess the success of plant breeding strategies (Condón *et al*., 2009).

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CHAPTER THREE

GENERAL MATERIAL AND METHODS

3.1 Research Design And Methodology

This section includes the study approach, experimental designs and data collection. The materials and methods used in this study are consistent across both localities, Heidelberg and Caledon. Any variations that were encountered will be specified in Chapter 4 and 5.

3.2 Study Methodology Approach

3.2.1 Trial site

Nine cultivars (Table 3.3) of winter barley were initially cultivated in the greenhouse of the South African Barley Breeding Institute (SABBI). All cultivars underwent multiplication in the greenhouse during the 2022 growing season. They were cultivated in a room equipped with 504 nursery pots, each measuring 150 mm in diameter and 170 mm in length. Three seeds were planted in each pot, and the growing medium utilized was pure sand. Irrigation was carried out using drip irrigation system with a balanced mixture of nutrients and water. The fertilizer mixture had a combination of Nutriplex and Nutrigrow, supplemented by a foliar application of Multifeed. The room temperature was maintained at 20 °C throughout the growing period. Additional illumination was provided by use of LED lights with a power output of 1000 watts operating 24 hours a day to influence photosynthesis rate.

The trials were planted in two localities (Caledon 34° 17' 35" south, 19° 30' 30" east and Heidelberg 34° 08' 54" south, 20° 44' 45" east) in the Western Cape Province in 2023 planting season. These localities are under rainfed and the soil type at Caledon and Heidelberg is clay loam which generally fall into the Hutton or Clovelly soil forms. Under rainfed production there is only one planting season per year which begins from April when the winter rainfall starts and ends in November. All cultivars that were used are two-row spring barley. Both trials were planted in most favourable planting condition. The trial in Heidelberg was planted on 5th May 2023 and harvested on 6th November 2023. The trial in Caledon was planted on 20th May 2023 and harvested on 17th November 2023.

3.2.2 Rainfall and temperature data for 2022, 2023 and five-years average.

All weather data including historical records was collected at the end of the year 2023 from an online platform (ARC ~ WEB DATA PORTAL (agroclimate.agric.za)) of ARC and Ab-InBev weather stations located in Caledon (34° 17' 40.0056" S, 19° 30' 44.7912" E) and Heidelberg (34° 12' 38.4" S, 20° 43' 50.988" E). Rainfall data (Figure 3.1), and maximum and minimum temperatures (Table 3.1) recorded during the 2023 growing season were compared with the 2022 and 5 years at Caledon.

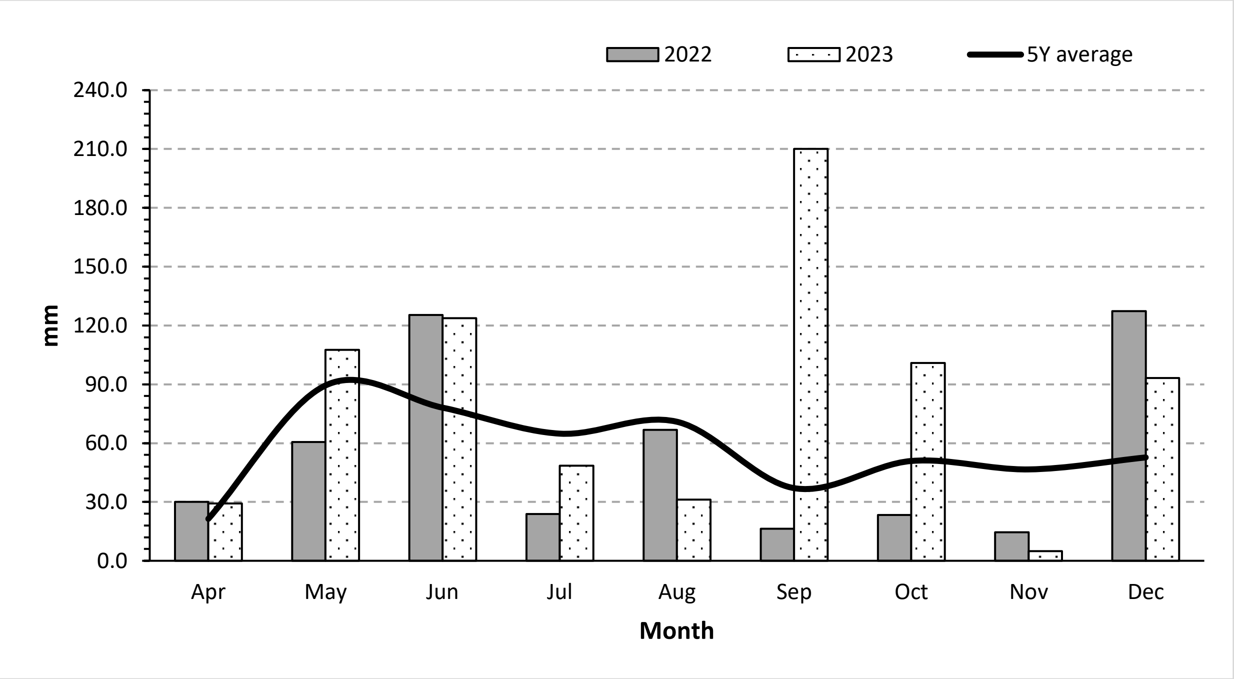

Figure 3. 1: Monthly rainfall (mm) from April to December during the 2023 growing season compared with the 2022 and 5 years' average growing season at Caledon.

Table 3. 1: Average monthly minimum and maximum temperatures during the 2023 growing season compared with the 2022 for Caledon.

Month	**2022 Season**		**2023 Season**	
	Min °C	**Max °C**	**Min °C**	**Max °C**
April	11.8	22.0	11.5	22.4
May	10.1	21.3	9.6	18.9
June	8.9	19.9	9.2	15.9
July	7.3	17.2	6.8	15.5
August	7.2	17.0	7.5	18.5
September	8.3	20.1	7.6	17.6
October	12.4	23.0	11.6	21.3
November	13.1	24.4	13.5	26.7
December	14.7	24.8	14.6	24.5

Rainfall data (Figure 3.2), and maximum and minimum temperatures (Table 3.2) recorded during the 2023 growing season were compared with the 2022 growing season averages at Heidelberg.

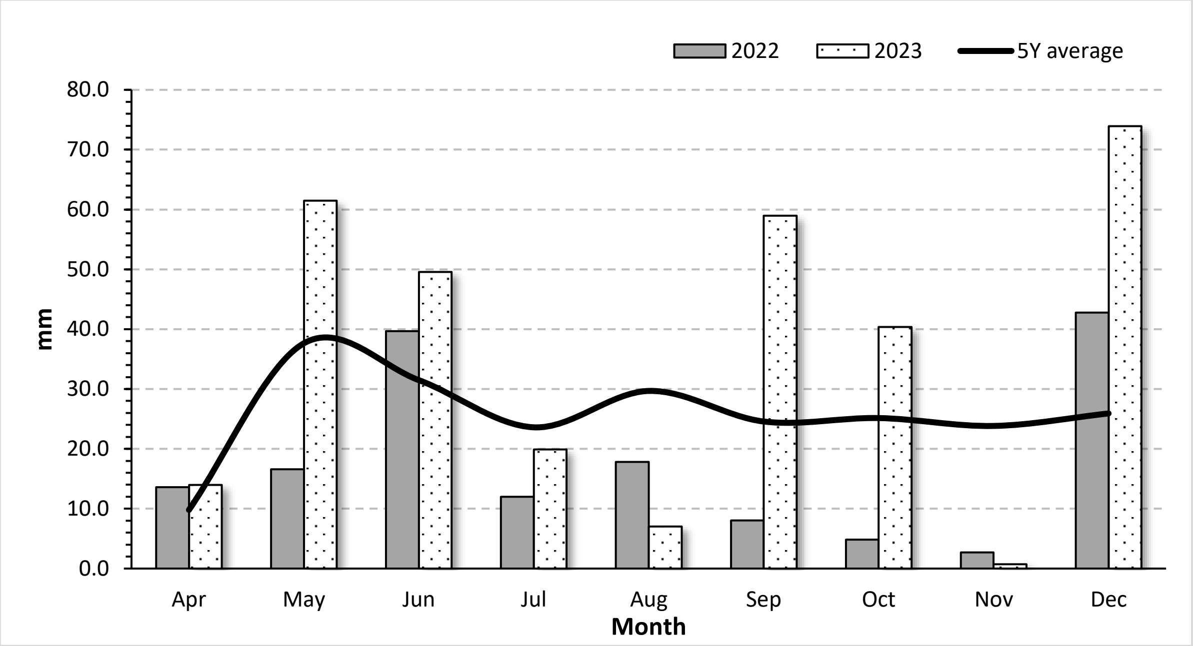

Figure 3. 2: Monthly rainfall (mm) from April to December during the 2023 growing season compared with the 2022 and 5 years' average growing season at Heidelberg.

Table 3. 2: Average monthly minimum and maximum temperatures during the 2023 growing season compared with the 2022 for Heidelberg.

Months	**2022 Season**		**2023 Season**	
	Min °C	**Max °C**	**Min °C**	**Max °C**
April	11.60	22.89	11.23	23.43
May	9.52	22.38	9.01	19.69
June	7.33	20.65	8.81	16.71
July	6.17	18.39	6.06	16.32
August	6.15	18.65	7.04	19.94
September	7.87	21.67	7.26	19.69
October	12.33	24.52	11.53	22.74
November	13.18	25.72	13.11	27.57
December	15.12	26.19	14.84	25.15

3.3 Experimental Designs

3.3.1 Trial layout

The trials were done using a randomised complete block design (RCBD). The plots were planted using a five-tine no-till deep blade plot planter. Each trial was planted in three replications of each entry and individual plots were 1.25 m width with an inter row spacing of 25 cm and 5 m in length with 5 rows per plot. The seeding density of 140 seeds m^{-2} was applied to different plots according to the thousand kernel weight (TKW).

All seeds were planted pure without any seed treatment. Fertilization of all the trials was applied according to the rainfed areas rotation system. Individual recommendations were based on the obtained soil analysis for both locations (Table 3.4). In both locations, two types of fertilizers were use through the growing season. At planting Alpha 36 fertilizer was applied and the first top dressing was done at 6-7 leaf stage with YarabelaTM CAN S. The second top dressing was done at flag leaf stage with YarabelaTM CAN S except Heidelberg.

Table 3. 3: Detailed overview of cultivar characteristics, seeding requirements and plots for sandy loam trial.

Cultivar	Year of release	Organization	TKW[1](g)	Seeds/m²	Kg/Ha	Grams/plot(g)	Plot area/m²	Soil type
Erica	2004	SABBI[2]	28	140	49	43	5 x 1.25	Sandy loam
Nemesia	2004	SABBI	33	140	58	51	5 x 1.25	Sandy loam
Disa	2006	SABBI	36	140	63	55	5 x 1.25	Sandy loam
Agulhas	2009	SABBI	34	140	60	53	5 x 1.25	Sandy loam
Hessekwa	2012	SABBI	41	140	72	63	5 x 1.25	Sandy loam
Elim	2014	SABBI	45	140	79	69	5 x 1.25	Sandy loam
Kadie	2016	SABBI	40	140	70	61	5 x 1.25	Sandy loam
Bitou	2019	SABBI	46	140	81	71	5 x 1.25	Sandy loam
Malgas	2020	SABBI	41	140	72	63	5 x 1.25	Sandy loam

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[1] Thousand kernel weight

[2] South African barley breeding institute

Table 3. 4: Fertilizer application type and the application level.

Locality	Application type	Product	Fertilizer level Kg/Ha			
			N	**P**	**K**	**S**
Caledon	Planting	Apha 36	25.2	16.8	8.4	6.4
	1st Top dressing	YaraBela CAN S	43.2	0	0	5.6
	2nd Top dressing	YaraBela CAN S	20.3	0	0	2.6
	Total		**88.7**	**16.8**	**8.4**	**14.6**
Heidelberg	Planting	Apha 36	25.2	16.8	8.4	6.4
	1st Top dressing	YaraBela CAN S	20.3	0	0	2.6
	2nd Top dressing	YaraBela CAN S	0	0	0	0
	Total		**45.5**	**16.8**	**8.4**	**9**

3.3.2 Pest management.

3.3.2.1 Weed management

Weeds were managed through the combination of manual removal, lawn mower and along with herbicide application. Weed control was achieved by the application before planting with the mixture of Trifluralin 480 EC at 2000 ml ha^{-1} and Makhro Paraquat at 3000 ml ha^{-1} followed by a mixture of Boxer at 3000 ml ha^{-1} and Bonanza 500 SC at 150 ml ha^{-1} immediately after sowing. Control of broadleaf weeds was done at 7 weeks after planting with a mixture of Brush off 3,5 g ha^{-1}, Quelex at 50 g ha^{-1}, 400MCPA at 750 ml ha^{-1}, and adjuvant Wetcit oro at 100 ml 100 litre^{-1}. Furthermore, an additional herbicide application was done at 7 weeks after planted for the control of Ryegrass with Axial at 200 ml ha^{-1} in Caledon. Maintenance of the trials i.e., spraying of alleys involved the use of Makhro Paraquat and manual removal of weeds in the plots by hand.

3.3.2.2 Disease and insect pest management

All trials received two applications of fungicide and insecticide. The first application was done at 5 weeks (5-6 leaf) after planting with a mixture of Ceriax at 800 ml ha^{-1} and Pyrinex 480 EC at 750 ml ha^{-1} and that was followed up by a mixture of Miravis at 800 ml ha^{-1} and Pyrinex 480 EC at 750 ml ha^{-1} at flag leaf stage. The insecticide that was selected (Pyrinex 480 EC) kills most of the common insects that appear on barley. It was used as a standard insecticide for trial purposes as this practice is cost-effective.

Table 3. 5: Pesticides used for the control of weeds, insects and fungal pathogens for all two localities.

Pesticide used for control	**Active ingredient**
Miravis (fungicide)	Adepidyn™ (pydiflumetofen)-200g litre^{-1}
Ceriax (fungicide)	Fluxapyroxad (pyrazole-carboxamide)- 41.6 g litre^{-1} Pyraclostrobin (methoxy-carbamate)-66.6 g litre^{-1} Epoxiconazole (triazole)- 41.6 g litre^{-1}
Pyrinex 480 EC (insecticide)	Chlorpyrifos-480 g litre^{-1}
Triflularin 480 EC (herbicide)	Dinitro analine-480 g litre^{-1}
Boxer (herbicide)	Prosulforcarb (thiocarbanate)- 800 g litre^{-1}
Bonanza 500 SC (herbicide)	Diflufenican (nicotinanilide)- 500 g litre^{-1}
Makhro Paraquat (herbicide)	Paraquat ion (bipyridyl)- 200 g litre^{-1} (as dichloride salt)- 276 litre^{-1}

3.4 Data Collection

3.4.1 Plant parameters

Plants were measured at full ear maturity on each plot using a tape measure to determine plant height. In each plot, plants were harvested in one meter at soil level by hand at the end of grain growth. The harvested plants were separated to enable plants m^{-1} and tiller $plant^{-1}$.

The number of plants m^{-1} was converted to plants m^{-2} using the following formulas:

- Plants m^{-2} = plants $m^{-1} \div 0.25$

The number of tillers m^{-1} was converted to determine tillers $plant^{-1}$ following formulas:

- Tillers $plant^{-1}$ = tillers $m^{-1} \div$ plants m^{-1}

3.4.2 Grain yield

At the end of the growing season, barley ears in the trial plots were harvested and threshed using a Wintersteiger Delta trial plot combine harvester. Following the harvest, the grain underwent a cleaning process and was then weighed. The grain yield kg ha^{-1} and yield gain in percentage was determined using the following formulas:

- Grain $_{(t/Ha)}$ $=\left(\frac{Sample\ weight\ (kg) X\ 10000}{1.25\ X\ 5}\right) \div 1000$
- Yield gain (%) $=\left(\frac{New\ variety\ (t\ ha-1) X\ Old\ vaiety\ (t\ ha-1)}{Old\ variety\ (t\ ha-1)}\right) \div 100$

4.4.3 Quality parameters

Nitrogen content of the kernels was determined with a Foss Infratec 1221 whole grain analyser. The complete grading was done on the harvested samples with a Steinecker grading apparatus. Grading was done using >2.5 mm sieve for kernel plumpness and < 2.0 mm sieve screenings. A working sample of 100 g of rubbed and un-screened barley was obtained from the consignment. Any stones present in the sample were manually removed. The sample was placed on a standard barley sieve, and then screened by moving the sieve 50 strokes to and from, alternately away from and towards the operator of the sieve, in the same direction as the long axes of the slots of the sieve. Data was analysed using Rstudio software (Version: 2023.09.1+494) and the results were statistically evaluated by the analysis of variance (ANOVA). A probability level of 5% was considered significant for all significance tests.

CHAPTER FOUR

GENETIC GAIN ON GRAIN YIELD AND AGRONOMIC TRAITS OF SELECTED BARLEY CULTIVARS IN THE WESTERN CAPE PROVINCE, SOUTH AFRICA.

4.1 Abstract

The demand of barley (*Hordeum vulgare* L.) for South Africa has been increasing over the years due to the increase of brewing industry. Barley breeders are working hard to make cultivars which will be able to grow in different climatic condition to spread the production. Barley can be bred to increase yield by improving parameter such as number of kernels ear^{-1}, ears m^{-2} and plant height. The objective of this study was to evaluate genetic gain on grain yield and agronomic traits of barley cultivars planted in a rainfed area. Field experiments with nine 2-row barley cultivars releases in different years from 2004 to 2020 was carried out using a complete randomized block design in two localities during the 2023 growing season. Lower yields were observed in Heidelberg due to water stress, whereas Caledon showed high yields. High yield was observed on a latest introduce cultivar Malgas (S20) with a yield of 6.17 t ha^{-1} and a lower yield of 3.20 t ha^{-1} was observed on the older cultivar Nemesia (S04). Similarly trend shortest plant height of 6.33 cm was recorded in Caledon on both Kadie (S16) and Malgas (S20). Heidelberg highlighted interesting results in genetic improvement. For example, the latest cultivar Bitou (S19) showed a lower plant density of 33 plants m^{-2} compared to the older cultivar Nemesia (S04) with 35 plants m^{-2}. However, Bitou demonstrated a higher ear density with 516 ears m^{-2} compared to Nemesia's 416 ears m^{-2}, indicating advancements in genetic traits contributing to enhanced yield potential. The main component associated with grain yield was the number of, due to the higher number associated to a greater contribution of the tillers in the modern cultivars.

Key words: Genetic gain, cultivar, grain yield

4.2 Introduction

The development of malting barley is needed as the world facing global warming which affects the growing conditions (Monteiro *et al.*, 2020; Simon *et al*., 2023; Grigorieva *et al*., 2023). Based on some scientific reports, it has been confirmed that weather and soil conditions play the most important role in determining the yield of malting barley **(**Bartosiewicz and Poręba, 2019; Simon *et al*., 2023). A good barley cultivar is recognized with it strong agronomic characteristics and quality malting parameters. Stronger investment on malting barley breeding programmes across South Africa is necessary, especially regarding the genetic improvement. The main objective of the introduction of new genetic characteristic in malting barley is to meet the demand for malt and offer farmers an alternative of diverse cultivars that grows in different climatic conditions more stable total grain yield and good quality of malt (Monteiro *et al.*, 2020). Higher grain yield is associated with shorter stem, higher harvest index, number ears per plant and kernels per ear (Cossani *et al*., 2022). The progress in genetic gain depends on the diversity in germplasm and the heritability of the desirable characters (Monteiro *et al.*, 2020).

In South Africa, barley breeding at SABBI began in 22 years ago, focusing on shortening plant height, resistance to diseases, tolerance to different environmental stresses, grain yield and malting quality (de Klerk 2023, personal communication). However, the effect of genetic gain of malting barley on yield components and quality parameters has not been reported making it difficult for the scientific community to understand the performance of malting barley under the unique growing conditions of South Africa. The breeding programme only relay on internal data to assess the genetic gain of malting barley. According to Cossani *et al.* (2022), plant breeding has increased the barley grain yield at rates between 0.4% year^{-1} and 1.1% year^{-1} in countries like Cananda, Italy, Nordic countries, Spain, and United State. The advance in genetic gain in these countries reflects the efficiency of the breeding process and the effect of the improved environmental conditions on grain yield (Rodrigues *et al.*, 2020). Yield increases achieved over the years has resulted from the impact of both genetic improvement and management practices (Yadav *et al*., 2021). The management practice has smaller contribution compared to the past as both environmental and economic reasons prohibit the increased use of chemicals (Abeledo *et al*., 2003). The objective of this study was to evaluate the genetic gain in grain yield and key agronomic characteristics across nine barley cultivars through comprehensive field trial and thereby providing insights into the progress achieved and potential areas for further breeding improvements.

4.3 Materials And Methods

The general materials used, and the methodology employed are presented in Chapter 3. Plants were measure in each plot at full ear maturity to determine plant height. In each plot, plants were harvested in one meter at soil level by hand at the end of grain growth. The harvested plants were separated to enable plants m^{-2}, ears m^{-2} and ears $plant^{-1}$. At the end of the growing season, barley ears in the trial plots were harvested and threshed using a Wintersteiger Delta trial plot combine harvester. Following the harvest, the grain underwent a cleaning process and was then weighed. Data collected were subjected to analysis of variance using RStudio (Version: 2023.09.1+494), where a significant difference was detected, variables mean were separated using Fisher’s protected least significant difference ($p<0.05$).

4.4 Results

4.4.1 Genetic gain on grain yield

Statistical analysis showed a significant difference between old and recently released cultivars ($p<0.05$) planted in Caledon on grain yield. This shows that the genetic gain significantly influenced grain yield on in different cultivars released in different years as shown in Figure 4.1. In a relative sense, the lowest grain yield was found on older cultivars and the highest grain yield was found on recently released cultivars. Cultivar Malgas (S20) which was released in

2020 showed a high yield of 6.17 t ha^{-1}, which was higher than all the yields observed in all localities and Erica (S04) which was released in 2004 showed a low yield of 3.92 t ha^{-1}. However, no significant difference on grain yield was recorded between Bitous (S19), Kadie (S16), Elim (S14), Hessekwa (S12) and Agulhas (S09).

No significant differences (*p>0.05*) were recorded in grain yield on all cultivars planted in Heidelberg. Looking into two distinct periods, the latest cultivars showed high yield compared to the older cultivars. Cultivar Malgas which was released in 2020 showed a grain yield of 4.50 t ha^{-1}, Hessekwa which was released in 2012 showed a grain yield of 3.54 t ha^{-1} and Nemesia which was released in 2004 showed a yield of 3.20 t ha^{-1}. These results show an increasing trend, even though increasing slightly from the older cultivars to recently released cultivars, it can therefore be noted that new cultivars have more grain yield than older cultivars.

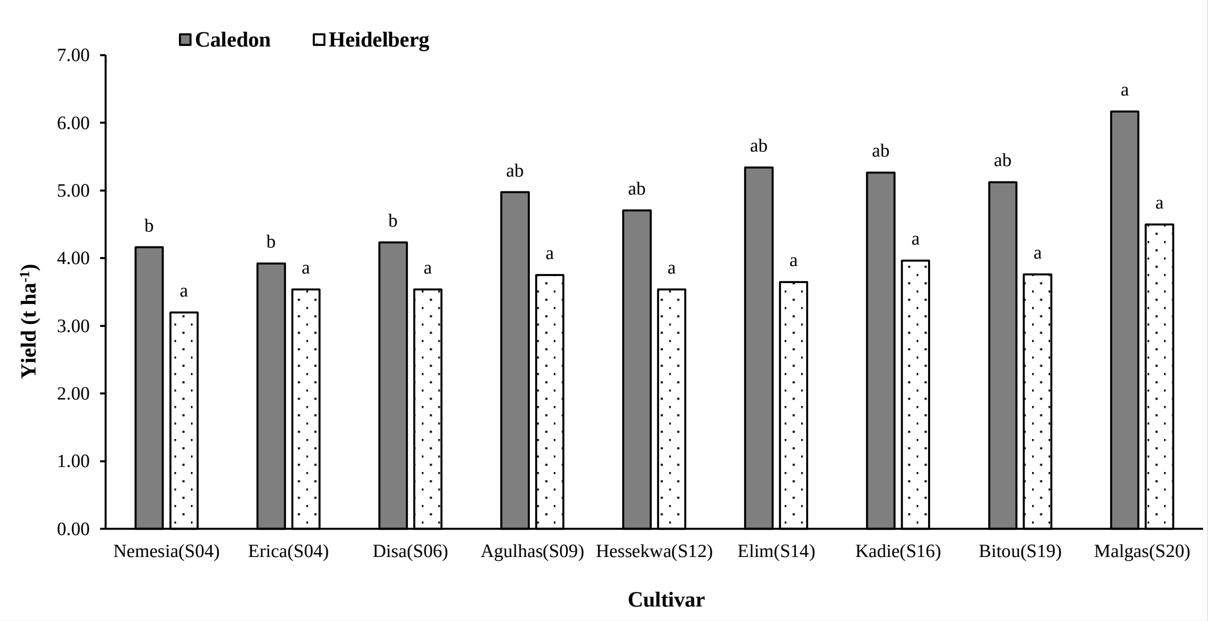

Figure 4. 1: Grain yield of barley cultivars released at different years at SABBI, where S04 (2004), S06 (2006) etc. represent a year in which each cultivar was released. Means represented by the same letter are not significantly different (*p>0.05*).

4.4.2 Genetic gain on plant height

In Caledon and Heidelberg, genetic improvement had interaction ($p<0.05$) with plant height of all cultivars. Caledon shows a significant trend of that older cultivars have high plant height and newer cultivars possess shorter height. No obvious trend was observed in Heidelberg in terms of shortening the plant height of cultivars released in different years.

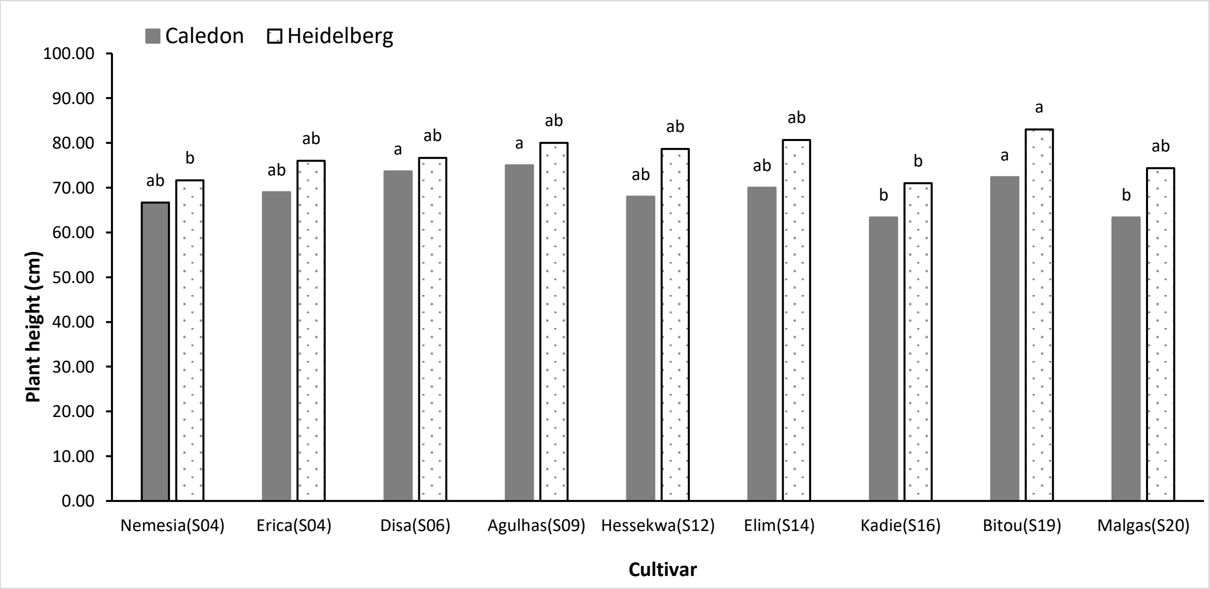

Figure 4. 2: Plant height of barley cultivars released at different years at SABBI, where S04 (2004), S06 (2006) etc. represent a year in which each cultivar was released. Means represented by the same letter are not significantly different ($p>0.05$).

4.4.3 Genetic gain on number of plants m^{-2}

The different cultivars released in different years had a significant difference ($p<0.05$) on plants m^{-2} in Caledon. The recent released cultivars had high plant counts where Malgas (S20) showed the highest plant count in all two localities. The highest plant count was observed from the cultivars, which was released in 2014 upwards to 2020, whereby the lowest plant count was observed from 2012 downwards to 2004. There were no significant differences ($p>0.05$) detected amongst all nine cultivars on plant counts m^{-2} in Heidelberg.

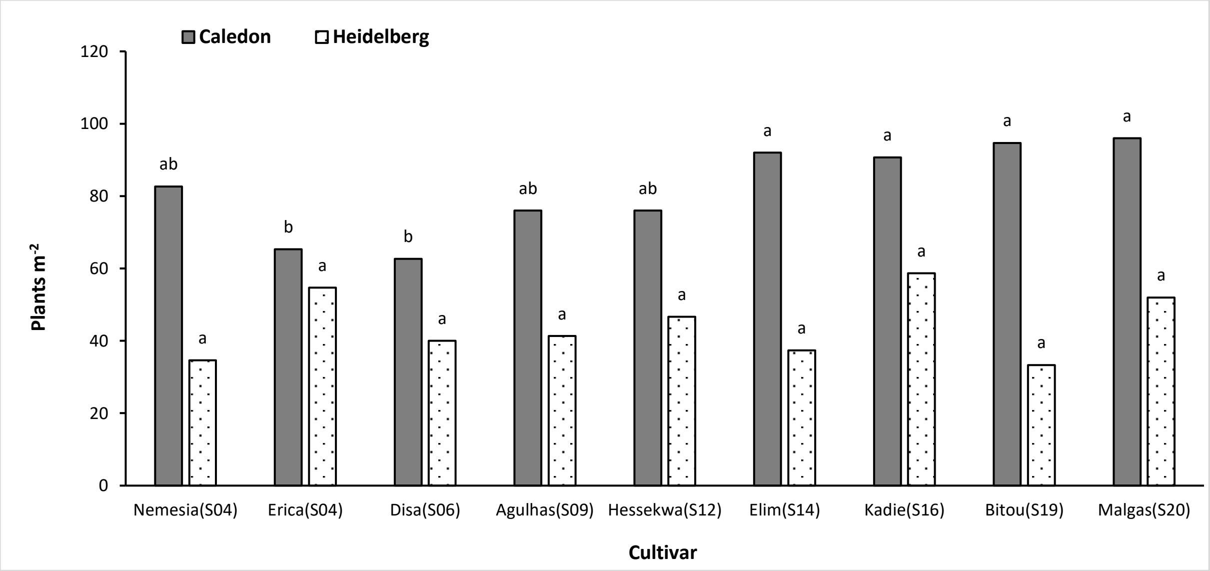

Figure 4. 3: Mean number of plants counted m^{-2} for nine different cultivars in two localities. where S04 (2004), S06 (2006) etc. represent a year in which each cultivar was released. Means represented by the same letter are not significantly different (*p>0.05*).

4.4.3 Effect of genetic gain on number of ears m^{-2}

The statistical analysis conducted on all cultivars planted in Caledon revealed a significant difference (*p<0.05*) in terms of ears m^{-2}. Older cultivars showed smaller numbers of ears m^{-2} compared to newer cultivars. Specifically, no significant difference was found among cultivars released from 2004 (Disa) to 2006. However, a significant difference was observed between cultivars released in 2006 and 2014 (Elim). No significant difference was found between cultivars released in 2014, 2016 (Kadie), 2019 (Bitou) and those released in 2020 (Malgas). In contrast, no significant difference in ears m^{-2} was observed among cultivars planted in Heidelberg, suggesting consistent or little difference in number of ears m^{-2} across all cultivars released in different years.

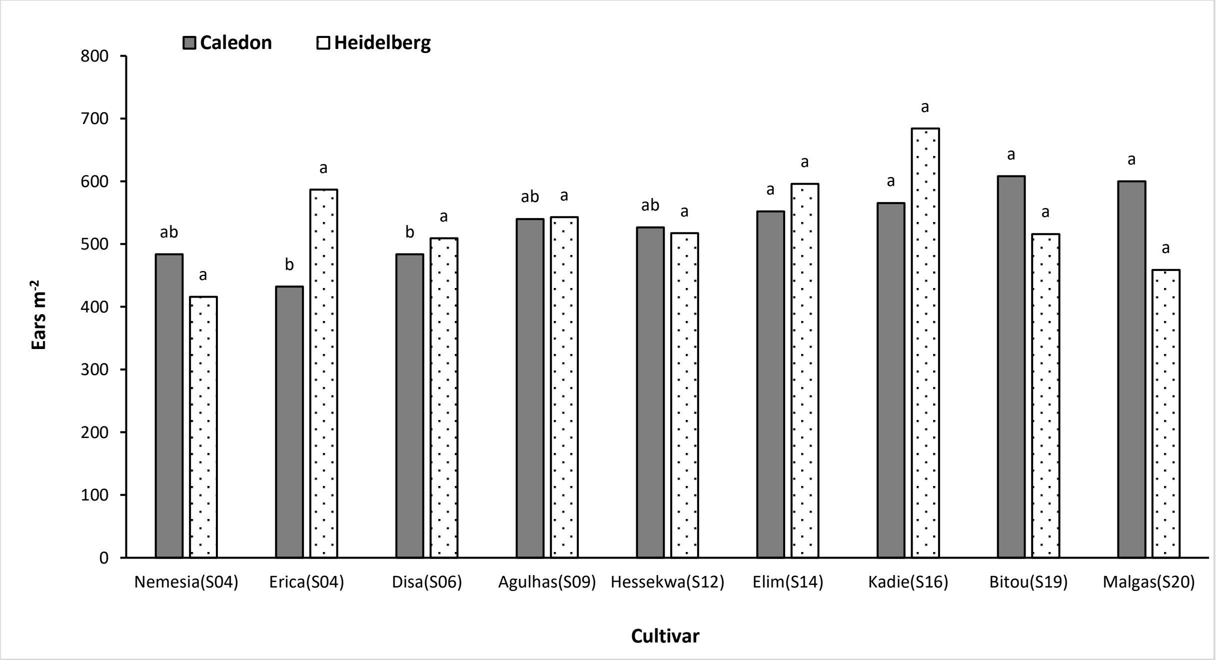

Figure 4. 4: Effect of genetic gain on number of ears m^{-2} of nine cultivars released in different years, planted in two localities. Where S04 (2004), S06 (2006) etc. represent a year in which each cultivar was released. Means represented by the same letter are not significantly different ($p > 0.05$).

4.5 Genetic Gain Relationship Analysis For Caledon And Heidelberg

4.5.1 Relationship between grain yield and plant m^{-2}.

There was a positive correlation between the number of plants counted and years of introduction of cultivars in Caledon and Heidelberg (Figure 4.5 and 4.6). The positive correlation is associated with genetic gain, suggesting that newer cultivars have genetic improvements for seedling establishment, stress tolerance, and disease resistance.

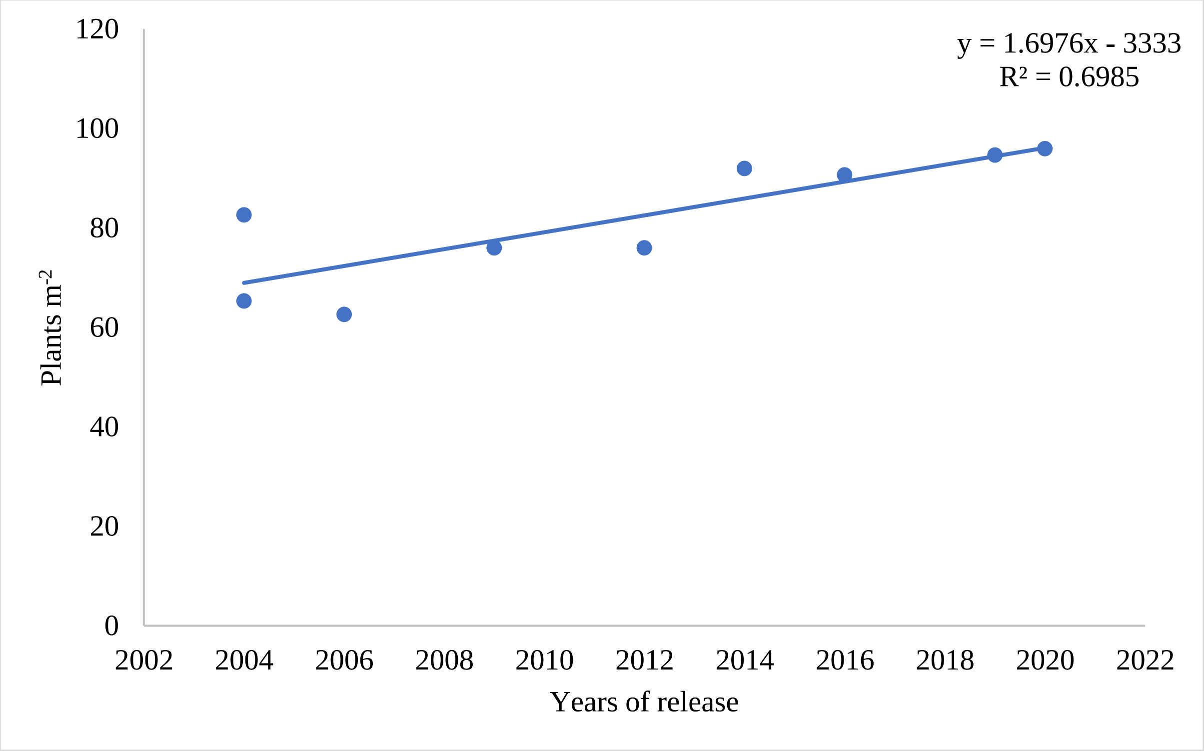

Figure 4. 5: Relationships between grain plant m^{-2} and year introduction of spring barley cultivars planted in Caledon.

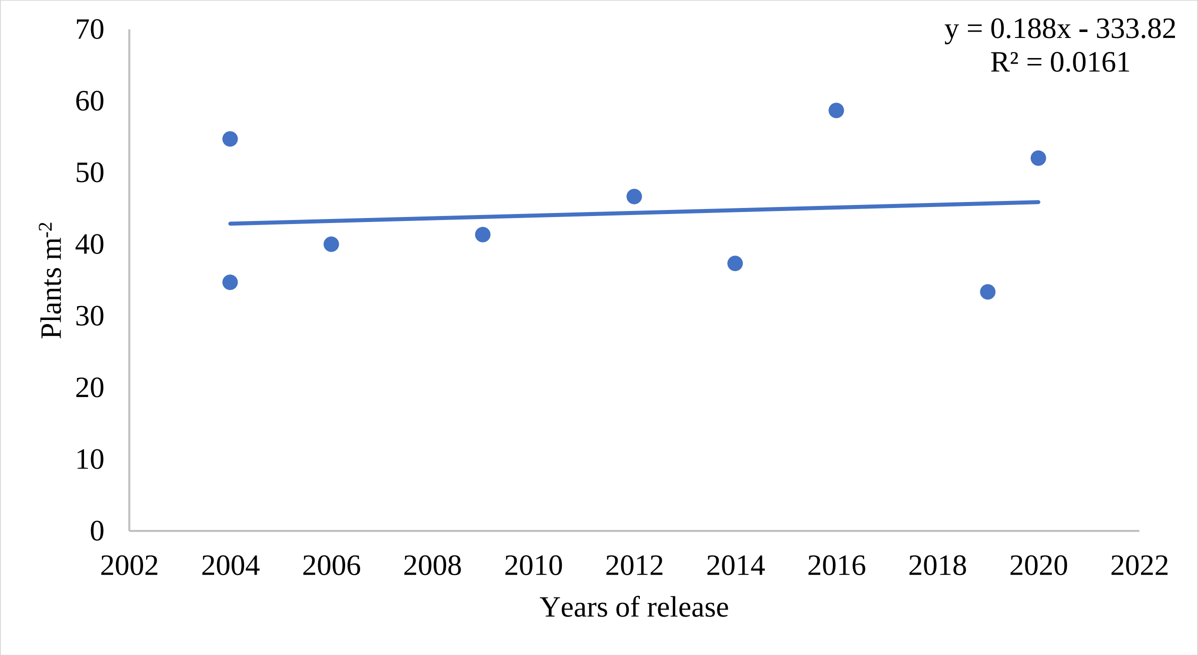

Figure 4. 6: Relationships between plant m^{-2} and year introduction of spring barley cultivars planted in Heidelberg.

4.5.2 Relationship between grain yield and ears m^{-2}

The correlation between ears count m^{-2} and years of introduction was positive in Caledon (Figure 4.7), whilst there was a slight small negative corelation observed in Heidelberg (Figure 4.8). It appears genetic improvements in newer cultivars are more evident in Caledon, a high-rainfall area, compared to Heidelberg, where limited rainfall may hinder their full potential..

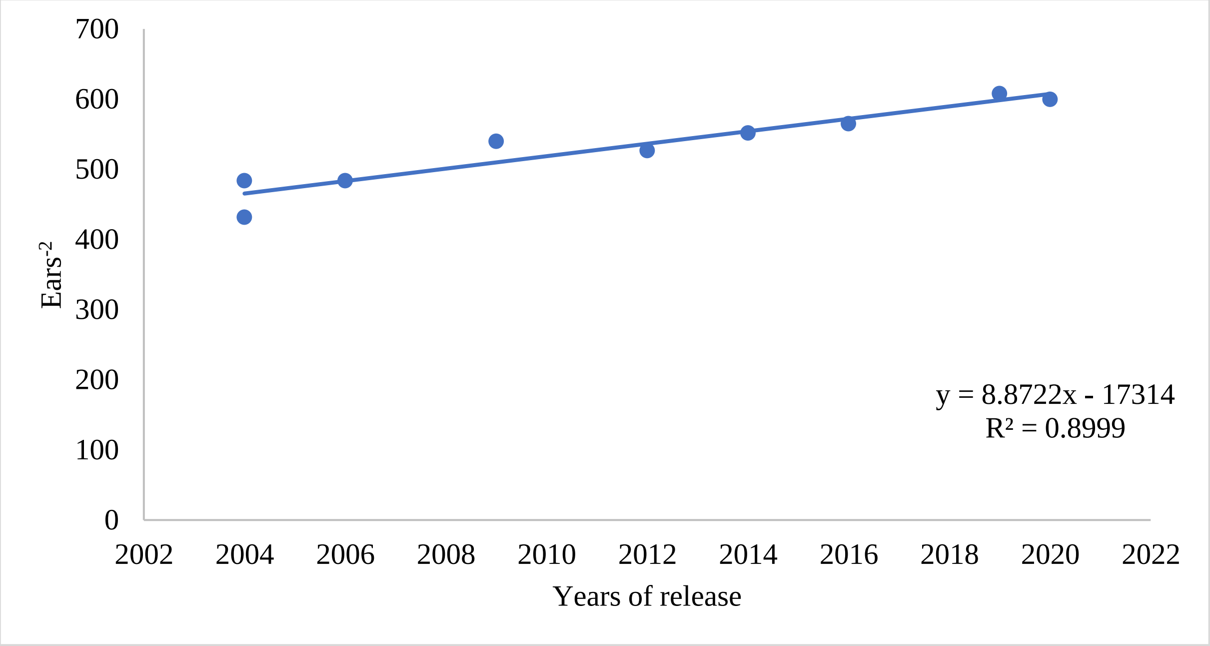

Figure 4. 7: Relationships between ears m^{-2} and year introduction of spring barley cultivars planted in Caledon.

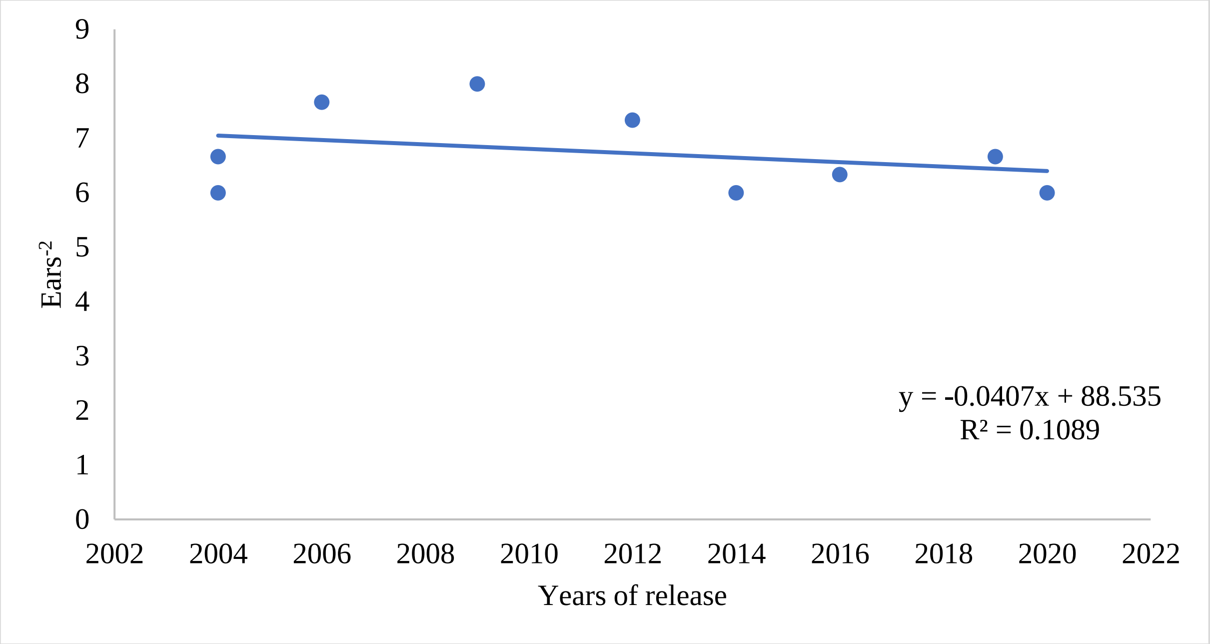

Figure 4. 8: Relationships between ears m^{-2} and year introduction of spring barley cultivars planted in Heidelberg.

4.6 Discussion

4.6.1 Weather conditions on plant establishments and grain yield

According to Simon *et al*. (2023) plant establishment is a starting point for the entire plant production cycle and can significantly influence grain yield and yield parameters. Plant establishment depends on soil and climatic conditions (Grigorieva *et al*., 2023). In 2023 season, soil was analysed, and fertilizer was applied according to the recommendations as provided in Chapter 3. Different climatic conditions were observed in during the season where trials were conducted. Rainfall for the 2023 growing season was above the 5 years average and 2022 growing season rainfall from April to December on both locations. In Caledon June had a rainfall of about 120 mm, which was more than enough for plant to produce enough tillers which were important for the number of ears m^{-2}, which also influence the number kernels ear^{-1} and intern result in high grain yield. For example, Caledon had the highest grain yield of 6.17 t ha^{-1} [Malgas (S20)] compared the all localities, with a minimum grain yield of 3.92 t ha^{-1} [Erica (S04)]. Heidelberg also had a good had start of high rainfall than the 5 years average in

May and June (Figure 3.2). High rainfall of 210 mm in Caledon and Heidelberg 60 mm which was observed in September affected the grain yield. The grain yield reduction was observed more in Heidelberg because it was planted early, and the plants were lodging which also resulted in mechanical damage during harvesting. For example, Heidelberg had a maximum yield of 4.50 t ha^{-1} [Malgas (S200)] with a lowest grain yield of 3.20 t ha^{-1} [Nemesia (S04)] compared to all localities. Weather data obtained from the weather stations positioned at different localities showed that rainfall increased after planting and started decreased gradually in July-August and increased during ripening to harvesting time. Inversely with temperatures, it was low at beginning of the growing season and increase gradually towards July-August and decreased again during ripening to harvest time (Figure 3.1 and 3.2).

4.6.2 Genetic gain on grain yield of different barley cultivars released in different years.

An increase in grain yield was noted during the initial decades of the 20th century, with a notable increase in the latter half, primarily due to advancements in genetics and practices (Rodrigues *et al.*, 2020). In this study a potential grain yield significantly differed among cultivars, ranging from a minimum of 3.20 t ha^{-1} to the maximum 6.17 t ha $^{-1}$ for all localities. The lowest yielding cultivar Nemesia which was released in 2004 was observed in Heidelberg with a grain yield of 3.20 t ha $^{-1}$. Even without any significant difference between all cultivars that were planted in Heidelberg. Grain yield showed a significant trend illustrating an increased in yield based on years of release with a result of modern cultivars producing more. Analysing the genetic gain in Caledon reveals distinct trends over seven periods based on the years cultivars were released. From 2004 to 2006, there was an 8% increase, followed by a 17% increase from 2006 to 2009. The period from 2009 to 2012 showed no increase, whereas from 2012 to 2014, there was a 13% increase. No increase was observed from 2014 to 2019, but a notable 20% increase occurred from 2019 to 2020. Similarly, in Heidelberg, there was no increase from 2004 to 2006, followed by a 6% increase from 2006 to 2009. Again, no increase was observed from 2009 to 2012, with a subsequent 3% increase from 2012 to 2014. From 2014 to 2016, there was a 9% increase, but no increase from 2016 to 2019, and finally, a significant 20 % increase from 2019 to 2020. In Fekadu *et al*. (2011) study, an increase in yield were observed for two cultivars, Balami and IAR/H/485. Specifically, for Balami, the findings indicated a substantial rise in yield, with increases of 302.44 kg ha^{-1} (9%), 735.98 kg ha^{-1} (22%), 1086.04 kg ha^{-1} (33%), and 1690.00 kg ha^{-1} (51%). Similarly, the cultivar IAR/H/485 demonstrated significant yield improvements, with increases of 12%, 22%, and 38%. Lalić *et al*. (2010) found a good selection on different criteria, where criteria Q12 was found to have a genetic improvement on grain yield plant^{-1} by 3%. Bulman *et al*. (1993) reported estimated rates of increase in grain yield over time, which ranged from approximately 0.25 to 0.27 t ha^{-1} year^{-1}. Abeledo *et al*. (2003) reported that, averaging across the century from 1944 to 1998, the estimated genetic gain in yield was equivalent to 20 kg ha^{-1} year^{-1} which represents a relative genetic gain of 0.36% year^{-1}. This consistent pattern is also evident in various studies of barley genetic gain, with grain yield serving as a key indicator of genetic improvement in barley cultivars (Abeledo *et al*., 2003; Rodrigues *et al.*, 2020; Cossani *et al.*, 2022).

4.6.3 Genetic gain on plant height

Barley breeding had an effect on genetic interaction in all cultivars bred at SABBI. In Caledon the cultivars which had a longer plant height were Disa (S06) with 73 cm, Agulhas (S09) with 75 cm and the decrease in plant height started to appear from 2012 on Hessekwas with 68 cm, then followed by the shortest significant cultivar Kadie (S16) with 63 cm and Malgas (S20) with 63 cm. This kind of trend shows that recently released cultivars contain a gene that is important for dwarf barley. This reduction in plant height shows the efficiency and applicability of good selection (Rodrigues *et al.*, 2020). Eshghi *et al*. (2011) study showed that a cross of ICNBF93-369×ICNBF-582 shows that plant height significant effects on grain yield and showed high heritability, this trait could serve as optimal indices for indirect selection for grain yield. Research literatures in genetic gain on barley also shows a similar trend to this study and they support the important of shorter plants which helps to reduce lodging that intern contributes to the advance in grain potential (Bulman *et al*., 1993). Plants had lodging in Heidelberg which also contributed reduction in grain yield. In this location no specific trend observed in term of shortening plant height for the cultivars released in different years. In this study the lowest grain yield of 3.20 t ha $^{-1}$ was observed on Nemesia (S04) cultivar which had a height of 76 cm, whilst the highest grain yield of 6.17 t ha^{-1} was observed on Malgas (S20) cultivar which had a height of 63 cm. These results portray a reduction of 13 cm between cultivar released in 2004 and cultivar released in 2020. In a study that was done in Brazil by Rodrigues *et al*. (2020) on genetic improvement of barley (*Hordeum vulgare* L) on yield increase and associated traits. Their results in the study showed barley height reduction rate of 1.0 cm year $^{-1}$. The reduction in plant height obtained by the breeding programmes should be monitored in the future to avoid the cultivation of cultivars with reduced heights that will negatively affect productivity due to a very dense canopy because such a condition may favour the development of foliar diseases and reduce the uniformity photosynthesis and biomass production ability. Lalić *et al*. (2010) found that direct selection for shorter stem length had a negative effect on grain yield plot^{-1} (18.99%) and the number of grains per spike (7.41%). According to a study that was done by Akgun (2016), plant height showed a genetic advance of 16.60% and was characterized by relatively high heritability. This means that a significant portion of the variation in plant height observed in the study population can be attributed to genetic improvement.

4.6.4 Genetic gain on grain yield components

The increase in grain yield in this study is linked to two main factors of an increase in the number of plants m^{-2} and the number of ears m^{-2}. The increase in maximum number of ears plant^{-1} and the number of kernels ear^{-1} is attributed to genetic improvements achieved through breeding efforts. This suggests that over time, the breeding program has been successful in enhancing this grain yield related traits. The interaction between barley cultivars and tillering pattern influences grain yield (Haaning *et al.*, 2020). Some cultivars show differences in tillering patterns and the percentage of tillers that survive to produce ears (Lalić *et al.*, 2010). Higher tillering capacity in a cultivar means that more tillers are produced per plant, which in turn can contribute to an increased number of ears m^{-2} (Kennedy *et al.*, 2017). Cultivars with a greater ability to produce tillers have a higher potential to develop multiple ears, thereby increasing the overall yield potential (Khumalo, 2019)

In both locations, it is evident that later released cultivars generally show a higher number of ears m^{-2} compared to older cultivars. In Caledon, cultivars released in 2019 and 2020 (Bitou - S19 and Malgas - S20) show notably greater plant densities than the older cultivar Erica (S04), with maximums of 94 and 96 plants m^{-2}, respectively compared to Erica's 65 plants m^{-2}. Conversely, in Heidelberg, the 2019 cultivar Bitou (S19) displayed the lowest plant m^{-2}, while an unexpected finding revealed that the 2004 released cultivar Nemesia (S04) show better adaptability to the dryer conditions of Heidelberg. Despite its earlier release, Bitou (S19) highlighted superior performance in terms of tillers and ears m^{-2} compared to Nemesia (S04), highlighting the efficacy of genetic improvements in later released cultivars. These results underscore the significance of both release year and genetic enhancement in determining the adaptability and productivity of barley cultivars across different environmental conditions. According to Fekadu *et al.* (2011) significant variation was observed in the number of ears plant^{-1} across barley cultivars, with a negative trend noted concerning the year of release, although not statistically significant in some cases. Abeledo *et al.* (2004) found that modern cultivars displayed relative improvement in the number of eras plant^{-1} compared to older cultivars. Similarly, no apparent trends were observed in grain number per main stem spike or tiller spikes per meter square between old and modern cultivars in another study (Bulman *et al.*, 1993). Additionally, Lalić *et al.* (2010) found that with a selection on different criteria, criteria

Q12 was found to have a genetic improvement on ears^{-1} by 4%. These findings collectively suggest complex dynamics regarding yield component traits in barley cultivars, with some improvements noted in modern cultivars compared to older ones, but without consistent trends over time across all studies (Abeledo *et al*., 2004; Lalić *et al*., 2010; Haaning *et al*., 2020).

4.7 Conclusion

The grain yield is affected by various factors such as plant m^{-2}, ear m^{-2}, and the amount of rainfall during the growing period. A comparison between Caledon, a region with higher rainfall and Heidelberg, a region with lower rainfall. Results revealed that Caledon generally had better grain yields in all cultivars compared to cultivars planted in Heidelberg. Across both locations, the newest cultivars consistently outperformed older ones, particularly those released between 2016 and 2020. The cultivar Malgas emerged as the top performer, yielding 6.17 t ha^{-1} in Caledon and 4.50 t ha^{-1} in Heidelberg. While Caledon showed a consistent trend in ear m^{-2}, Heidelberg demonstrated advancements in genetic traits, as seen in the comparison between the latest cultivar Bitou and the older cultivar Nemesia. Despite Bitou having a lower plant density, it exhibited a higher ear density, indicating improvements in genetic traits leading to increased yield potential.

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CHAPTER FIVE

GENETIC GAIN ON MALTING QUALITY OF SELECTED BARLEY CULTIVARS IN THE WESTERN CAPE PROVINCE, SOUTH AFRICA.

5.1 Abstract

This study assesses the genetic gain in malting barley (*Hordeum vulgare* L.) quality over time in South Africa, focusing on nine cultivars released by the South African Barley Breeding Institute (SABBI) between 2004 and 2020. The experiment was conducted under rainfed conditions in two different localities Caledon and Heidelberg in 2023. A randomized completely block design (RCBD) was used and grain samples were analysed for kernel total nitrogen content and graded based on kernel plumpness (>2.5 mm sieve) and screenings (< 2.0 mm sieve). The results showed contrasting trends in total nitrogen content across the two locations, with Caledon showing a positive relationship between total nitrogen and years of release ($y = 0.0088x - 16.167$), whereas Heidelberg showed a negative relationship ($y = -0.0045x + 10.872$). Plumpness showed consistent improvement over time, with the latest cultivar Bitou (S19) demonstrating the highest plumpness in both locations (Caledon: 95.82%, Heidelberg: 96.97%). However, significant differences and negative relationships were observed in screenings in both Caledon ($y = -0.192x + 390.1$, $p<0.045$) and Heidelberg ($y = -0.0594x + 120.62$, $p<0.041$). Statistical analyses were performed using Rstudio software (Version: 2023.09.1+494), and significance was determined using analysis of variance (ANOVA) with a probability level of 5%. These findings contribute to understanding the success of the breeding programme in enhancing malting barley quality in South Africa under rainfed.

Keywords: Genetic gain, Breeding, Malting barley, cultivar

5.2 Introduction

Barley (*Hordeum vulgare* L.) stands as the backbone of the malt production industry, used globally for its exceptional inbred qualities (Rani and Bhardwaj, 2021; Trubacheeva and Pershina, 2021; Smith *et al*., 2021; Jones *et al*., 2021). Beyond mere productivity, the standards for barley intended for malting are exacting demanding a moisture content below 13.5% and protein levels within the 9.5% to 12.5% range (O'Donovan *et al*., 2011). Moreover, variety purity, uniform kernel size, and the absence of screenings such as peeled, broken, or damaged kernels are non-negotiable requirements (Therrien *et al*., 1994). Barley's journey from grain to malt is transformative with-it quality traits playing an important role (Rooney *et al*., 2023; Brown *et al*., 2021). Its quality is importance in the brewing industry where malt serves as a fundamental ingredient (Rooney *et al*., 2023; Holm *et al*., 2018). Barley important role in brewing has elevated it to the status of an industrial crop, attracting attention from entrepreneurs, farmers and researchers (Rani and Bhardwaj, 2021; Trubacheeva and Pershina, 2021; Smith *et al*., 2021).

Optimizing malt extract production depends upon using different method and approaches that needs to consider grain parameters such as size, shape, moisture, protein content and yield (Rooney *et al*., 2023; Holm *et al*., 2018). Breeding superior barley cultivars remains central to these endeavours, with a dual focus on enhancing malting quality and maximizing yields (Xue *et al*., 2020). Innovative breeding strategies have demonstrated significant genetic gain in improving malt quality traits over time (Zhang *et al*., 2021). These efforts have led to the identification of genetic markers associated with desirable characteristics such as high enzymatic activity, low β-glucan content, and improved starch composition, facilitating targeted breeding for superior malting quality (Wenzl and Carling, 2020). However, this pursuit is not without challenges, as high yields often correlate with undesirable traits such as elevated protein and β-glucan content (Trubacheeva and Pershina, 2021). Notably, the depletion of genetic diversity and the presence of climate change have prompted a re-evaluation of traditional breeding strategies, with an increasing interest in winter barley varieties (Trubacheeva and Pershina, 2021). In this quest for better barley, modern breeding methodologies offer promising avenues for accelerated plant selection and translate the genetic foundation of malt quality traits (Zhang *et al*., 2021). By integrating traditional breeding practices with innovative genetic insights, the barley industry paves the way for cultivating varieties that seamlessly blend high yields with impeccable malt quality, ensuring a continuous of excellence in malt production worldwide (Wenzl and Carling, 2020).

5.3 Materials And Methods

For a detailed description of the general materials used and the methodology employed, please refer to Chapter 3 of this study. The methodology was implemented to ensure accurate assessment of nitrogen content, kernel plumpness, foreign matter, and screenings in the barley, thereby providing reliable data for analysis and interpretation.

5.4 Results And Discussion

5.4.1 Genetic gain on total nitrogen

According to Khumalo (2019), the South African standards for malting barley, emphasizing a total nitrogen content range of 1.5% to 2.0% for malt delivery. Moreover, Venter (2024, personal communication) highlights the implementation of premium rates for malting barley falling within the narrower range of 1.56% to 1.85% total nitrogen content, reflecting the industry's recognition of quality thresholds. In the analysis, where the years of release of cultivars are denoted by, for example, S04 (2004), S06 (2006), it is evident that modern cultivars demonstrate a higher total grain nitrogen content compared to older cultivars, ranging from 1.51% to 1.90% for both trials. In the Caledon area, there is a positive correlation ($y = 0.0088x - 16.167$) between total grain nitrogen content and the year of release of the cultivars, as showed in Figure 5.1. Statistical analysis showed a significant difference ($p<0.05$) in total grain nitrogen content among cultivars released in different years. The lowest nitrogen content is recorded in the cultivar Nemesia (S04) at 1.51%, whereas the highest is observed in Bitou (S19) at 1.72%. This trend reveals that older cultivars tend to have lower grain nitrogen content, while newer ones display higher levels. Malting barley with protein content below 10% may not provide adequate Free Amino Nitrogen (FAN) necessary for yeast growth, potentially leading to fermentation issues (Kumar *et al*., 2013; Luo, 2019). On the other hand, higher protein content in malting barley contributes positively by enhancing foam stability and influences negatively by increased haze formation in beer (Rani *et al*., 2021). Furthermore, malting barley exceeding 12.5% protein content equivalent to 2% nitrogen content, is deemed undesirable due to its negative correlation with malt starch levels and extract value, which can adversely impact brewing efficiency and final product quality (Luo, 2019). Hence, to fulfil the quality standards demanded by maltsters, barley grains must possess appropriate nitrogen content content (Rani *et al*., 2021). In the Caledon area, cultivars falling within the lower premium band of 1.56% to 1.60% total grain nitrogen content include Erica (S04) at 1.58 % and Agulhas (S04) at 1.58%. Those within the higher premium band of 1.61% to 1.80% total grain nitrogen content comprise Hessekwa (S12) at 1.66 %, Elim (S14) at 1.65%, Kadie (S16) at 1.62%, Bitou (S19) at 1.72%, and Malgas (S20) at 1.65%.

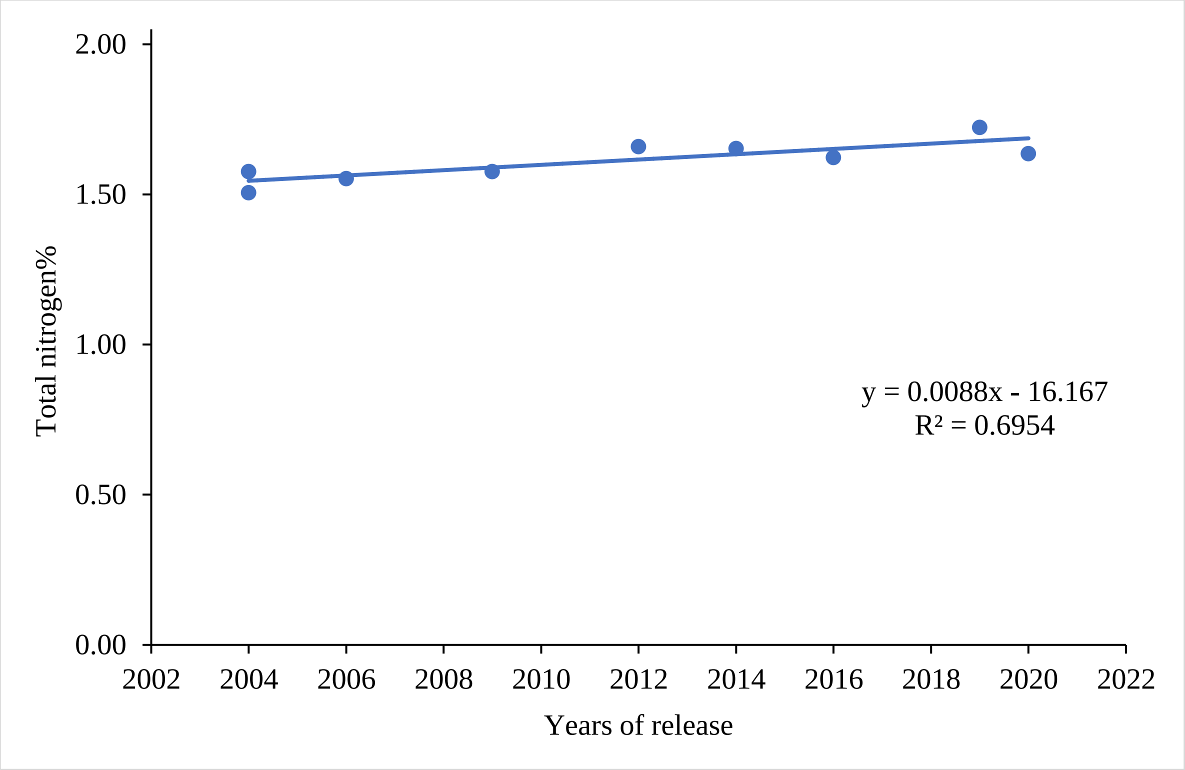

Figure 5. 1: Relationships between kernel total nitrogen and year of introduction of nine cultivars of spring barley planted in Caledon.

In Heidelberg, contrasting results are observed, with high grain nitrogen content noted. The cultivar Elim (S14) highlights the minimum grain content at 1.78%, while Erica (S04) records the maximum at 1.99%. The analysis reveals a negative association between the years of cultivar release and total grain nitrogen content, as showed in Figure 5.2. The relatively elevated average total grain nitrogen content in this locality may be attributed to the limited rainfall during the season. Furthermore, statistical analysis indicates a significant difference ($p<0.05$) in total grain nitrogen content among cultivars released in different years. Notably, Erica (S04) and Elim (S04) display significant variations. All cultivars are within the malting specifications ranging from 1.5% to 2.1% total grain nitrogen content. Additionally, several cultivars fall within the premium bands, which range from 1.56 % to 1.85%. In Heidelberg, most cultivars do not fall within any premium band on the total grain nitrogen content sliding scale. Only Kadie (S16) at 1.84% falls within the lower premium band of 1.81% to 1.85%, while Hessekwa (S12) at 1.80% and Elim (S14) at 1.78% are within the higher pay premium band.

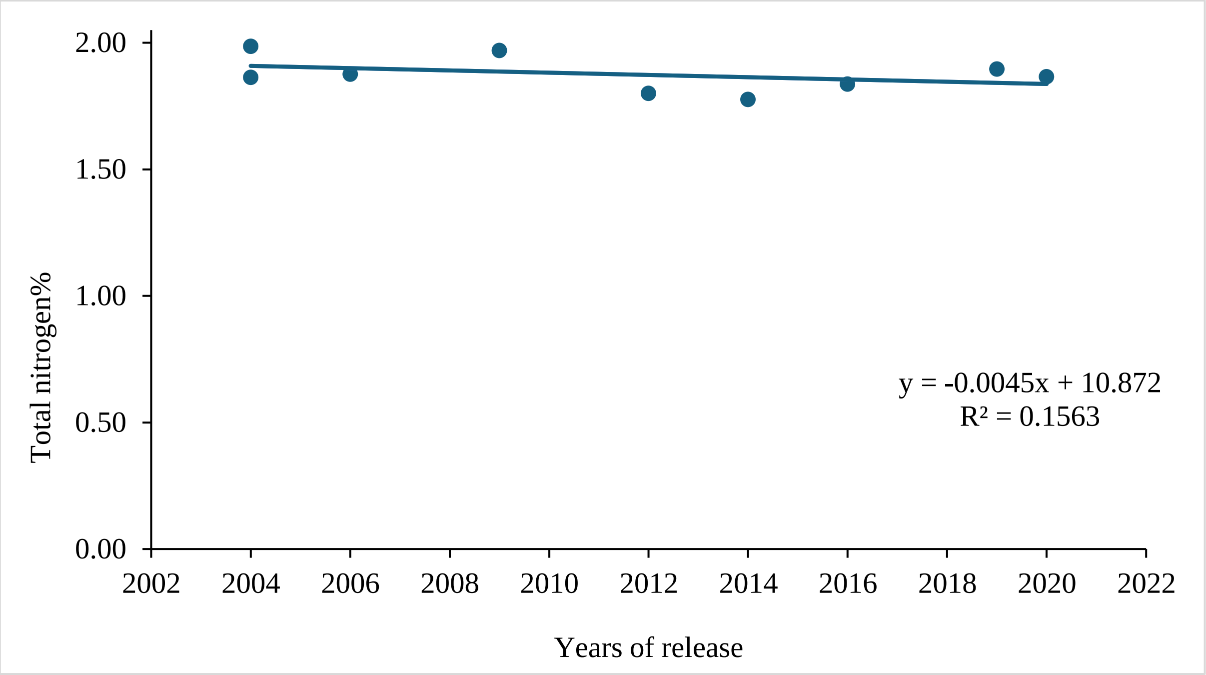

Figure 5. 2: Relationships between kernel total nitrogen and year of introduction of nine cultivars of spring barley planted in Heidelberg.

The results highlight a concern regarding older cultivars exhibiting total grain nitrogen content that is either too high or too low, posing challenges for breweries. Genetic improvement programs have been instrumental in enhancing the total nitrogen content of barley cultivars, thereby contributing to brewing quality and efficiency (Luo *et al*., 2019). According to Trubacheeva and Pershina (2021) study, Marker-assisted selection is effective in incorporating QTLs into populations, even when only one parent is initially used for QTL identification and mapping. Using SSR markers, they introduced QTL regions for protein content from the winter malting barley Nure into a double haploid population resulting from crossing Nure with the spring malting variety Tremois. This process led to the development of SSR markers flanking QTLs located on chromosomes 2H, 6H, and 7H. These loci showed a significant impact on protein content, suggesting their potential utility in breeding programs aimed at developing varieties with high protein content. The genetic enhancement of varieties to achieve optimal nitrogen content has enabled brewers to consistently produce high-quality malt with desirable brewing characteristics (Rani *et al*., 2021).

5.4.2 Genetic gain on plumpness

The findings from the Caledon trial showed positive relationship between kernel plumpness and the years of release of cultivars (Figure 5.3). The newer cultivars showed a greater kernel plumpness when compared with their older cultivars. The required plumpness for malting barley typically varies depending on specific quality standards and industry preferences (Rani *et al*., 2021). However, malting barley often needs to have a plumpness level of at least 80% or higher to meet the standards for malting and brewing purposes (Fox *et al*., 2008). Homogeneous water uptake and grain modification are facilitated by larger, uniform kernel sizes (Kumar *et al*., 2013). In Caledon, Bitou (S19) and Kadie (S16) stood out as leading cultivars in terms of plumpness demonstrating percentages of 95.82% and 93.03%. Cultivar Agulhas (S09) and Hessekwa (S12) showed a comparatively lower plumpness percentage, standing at 84.67% and 85.02%, respectively. The difference in plumpness between cultivars released in 2009 and 2016 was 11.15%.

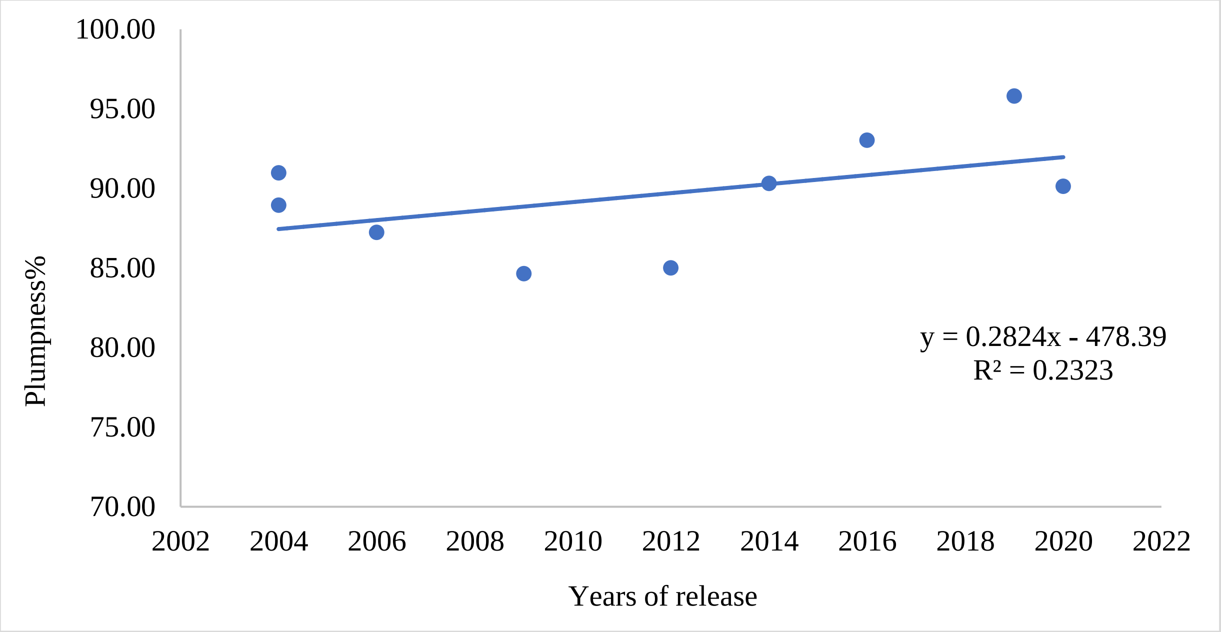

Figure 5. 3: Relationships between kernel plumpness and year of introduction of nine cultivars of spring barley planted in Caledon.

Similarly, the Heidelberg trial showed a positive relationship between kernel plumpness and release years of cultivars (Figure 5.4). Notably, Bitou (S19) continued to show a remarkable plumpness reaching 96.97%, while Kadie (S16) maintained its high plumpness at 96.28%. Conversely, Erica (S04) and Hessekwa (S12) showed lower plumpness percentage in Heidelberg, standing at 93.97% and 94.17%. The variation in plumpness between cultivars released in 2004 and 2019 in Heidelberg was measured at 3.88%. The number of rows of kernels on the barley spike is a crucial factor influencing the size, shape, and uniformity of barley kernels (Kumar *et al.*, 2013). Collectively, while Heidelberg showed a higher average plumpness compared to Caledon, both localities demonstrated a consistent trend towards genetic enhancement in kernel plumpness over time.

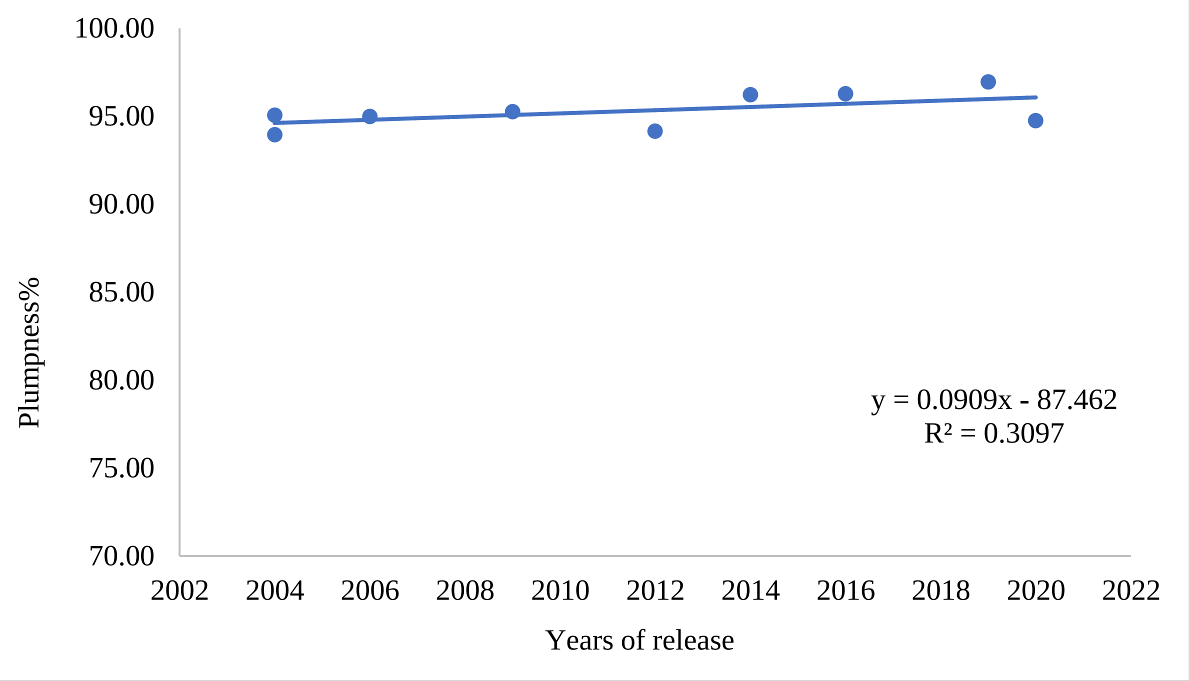

Figure 5. 4: Relationships between kernel plumpness and year of introduction of nine cultivars of spring barley planted in Heidelberg.

5.4.3 Genetic gain on screenings

In both Caledon (Figure 5.5) and Heidelberg (Figure 5.6), the statistical analysis revealed a significant difference ($p<0.05$) and a negative correlation between screenings and cultivars released in different years. This negative relationship indicates a gradual decrease in screenings percentage across successive cultivar releases. In Caledon, the highest screenings were recorded for Disa (S06) at 7.04% and Hessekwa (S12) at 5.38%. Conversely, Bitou (S19) showed the lowest screening percentage at 1.50%, followed by Malgas (S20) at 2.55%. The decline in screening percentage from the cultivar released in 2006 to that in 2020 amounted to 4.85%.

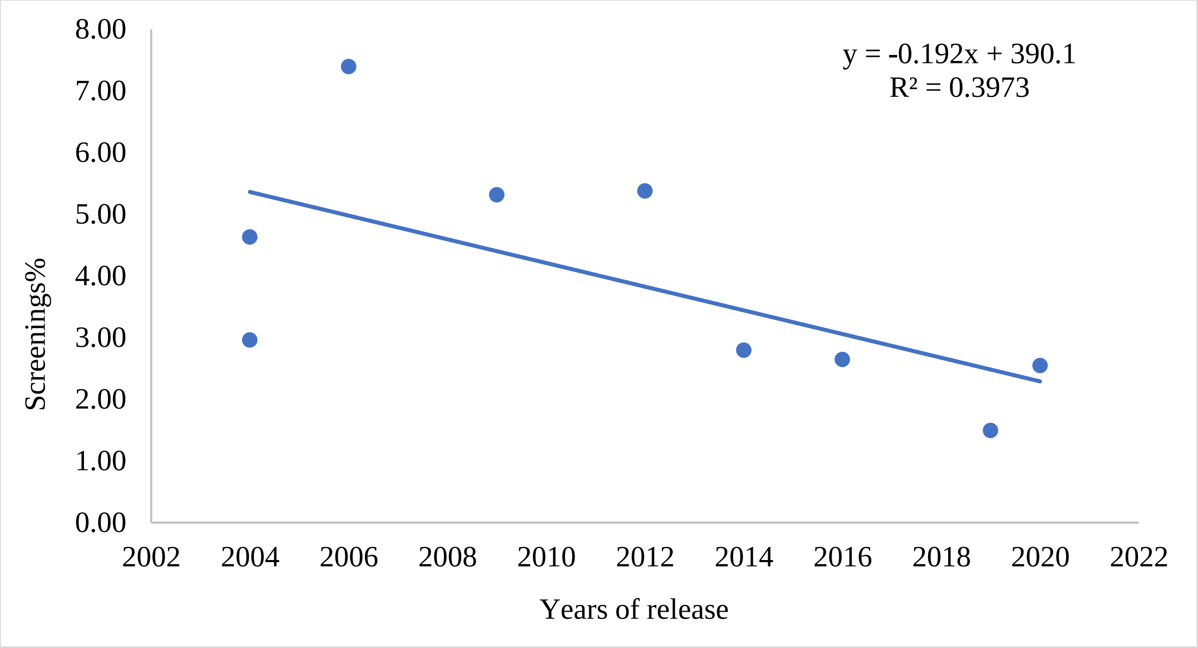

Figure 5. 5: Relationships between screenings and year of introduction of nine cultivars of spring barley planted in Caledon.

In Heidelberg, Nemesia (S04) and Erica (S04) showed the highest screenings at 1.53% and 1.80%, respectively. On the other hand, Elim (S14) and Malgas (S20) showed the lowest screenings at 0.62% and 0.63%. The decline in screening percentage from the average of cultivars released in 2004 to those released in 2020 was 1.17%. In Heidelberg, Nemesia (S04) and Erica (S04) showed the highest screenings at 1.53% and 1.80%, respectively. On the other hand, Elim (S14) and Malgas (S20) showed the lowest screenings at 0.62% and 0.63%. The decline in screening percentage from the average of cultivars released in 2004 to those released in 2020 was 1.17%. Many studies like Rodrigues *et al*. (2020), Fekadu *et al*. (2011) and Abeledo *et al*. (2003) have shown that malting quality can be improved by breeding, although they do not specifically focus on screenings. Overall, the various breeding methods and techniques explored in these studies may indirectly contribute to reducing screenings by improving overall plant health, grain quality, and uniformity in barley.

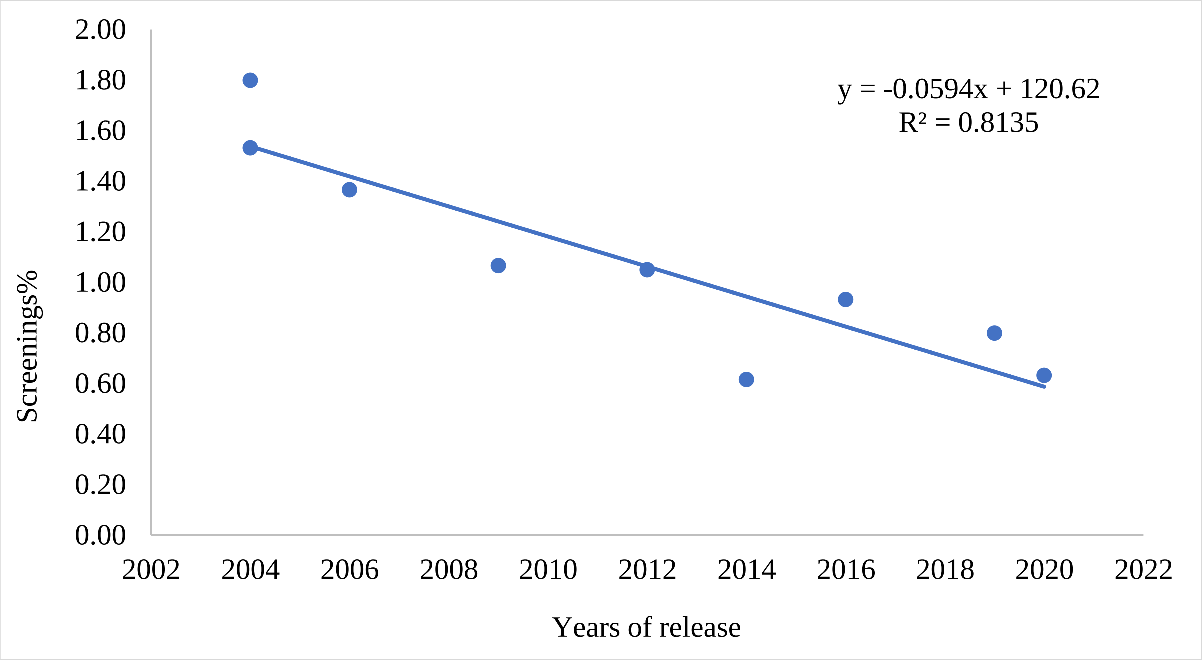

Figure 5. 6: Relationships between screenings and year of introduction of nine cultivars of spring barley planted in Heidelberg.

5.6 Conclusion

Quality improvement is observed across all locations, with newer varieties consistently showing better and more consistent quality compared to older varieties. The total grain nitrogen content ranges from 1.51% to 1.90%. In Heidelberg, the highest nitrogen content of 1.99 % was observed in Erica (S04), while the lowest of 1.51% was observed in Nemesia (S04). In terms of plumpness, the variety Bitou, introduced in 2019, stood out in both locations with an average of 96.4%. A decrease in screenings was observed in both locations, with all the latest varieties showing a decline. The lowest screenings were observed in Malgas at 0.63% in Heidelberg, while the highest screening of 7.40% was seen in Caledon on the cultivar Disa (S06). While recent studies have shown promising results in enhancing various quality traits such as grain nitrogen content, plumpness, and screenings, there is still room for improvement. Future research should focus on identifying and incorporating new genetic factors associated with quality traits, optimizing breeding strategies to achieve desired quality outcomes, and evaluating the performance of newly developed varieties across different environments and management practices.

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CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General Discussion

The current study emphasizes the significant role of breeding in improving malting barley production by focusing on developing cultivars with high grain yield, lodging resistance, and superior malting quality. It also highlights the influence of varying rainfall patterns on the yield and quality of barley varieties. For instance, in Caledon, where the highest yield reached 6.17 t ha^{-1}, rainfall was 749 mm, while in Heidelberg, the maximum yield was 4.50 t ha^{-1} with a total rainfall of 326 mm. Furthermore, the study reveals variations in grain yield among cultivars released in different years. Newer cultivars demonstrated higher grain yields compared to older ones, as shown in Figures 4.1 and 4.2. The Malgas cultivar released in 2020, showed superior performance in both localities, reflecting the positive impact of recent breeding advancements on yield improvement. These findings align with previous research of Bulman *et al*. (1993) who they observed an annual increase in barley yield ranging from 0.25 to 0.27 t ha^{-1}, while Abeledo *et al*. (2003) reported a genetic gain of 20 kg ha^{-1} year^{-1}, representing a relative improvement of 0.36% year^{-1}. Similarly, Lalić *et al*. (2010) found a genetic improvement in grain yield per plant by 3%. There was no clear trend on reducing plant height in all varieties for both locations in this study. The lowest grain yield of 3.20 t ha^{-1} was observed on Nemesia (S04) cultivar which had a height of 76 cm, whilst the highest grain yield of 6.17 t ha^{-1} was observed on Malgas (S20) cultivar which had a height of 63 cm. Eshghi *et al*. (2011) study showed that plant height significant had an effects on grain yield and showed high heritability of which this could serve as optimal indices for indirect selection for grain yield.

The higher total nitrogen content in newer cultivars suggests genetic enhancement efforts have been successful in increasing nitrogen levels in barley grains over time. This improvement is essential for brewing quality, as optimal nitrogen content contributes to desirable brewing characteristics (Rani *et al*., 2021). However, the study also revealed contrasting trends in total nitrogen content across locations, indicating the influence of environmental factors on nitrogen accumulation. The positive correlation observed in Caledon suggests that breeding efforts have effectively increased nitrogen content, while the negative correlation in Heidelberg may be attributed to environmental conditions such as limited rainfall.

Kumar *et al*. (2013) state that barley with higher plumpness allows for more uniform water uptake and grain modification during the malting process, resulting in improved malt quality. The study observed consistent improvement in plumpness over time, with newer barley cultivars generally exhibiting higher plumpness compared to older ones. For instance, the latest cultivar, Bitou (S19), demonstrated the highest plumpness in both localities, with percentages reaching 95.82% in Caledon and 96.97% in Heidelberg. This trend indicates the effectiveness of breeding efforts in enhancing barley grain plumpness. Thus, breeding for enhanced plumpness should be prioritized to ensure the continued production of high-quality malt barley (Fox *et al*., 2008). The decline in screening percentage from older cultivars to newer releases underscores the effectiveness of breeding efforts in improving barley quality over time. For example, in Caledon, the decline in screening percentage from cultivars released in 2006 to those released in 2020 amounted to 4.85%, while in Heidelberg, it was 1.17%. This consistent reduction in screenings across different regions and years suggests that breeding programs have successfully targeted traits associated with reduced screenings, such as grain plumpness and uniformity.

6.2 Conclusions

The study observed a significant difference ($p<0.05$) in grain yield among cultivars released in different years in the Caledon trial, while no significant difference ($p>0.05$) was found in the Heidelberg trial. In both locations, there was a noticeable trend of increasing grain yield, with older varieties exhibiting lower yields and newer varieties showing higher yields.

The study observed a positive correlation between total kernel nitrogen content and the release years of cultivars in Caledon, while a negative correlation was found in the Heidelberg trial. Despite these correlations, all varieties evaluated in both locations fell within the acceptable range of 1.56% to 2.0% for total kernel nitrogen content.

With regards to plumpness, all varieties exhibited consistently high plumpness above 80%, meeting the malting acceptance criteria. The results showed a positive correlation for both localities, with plumpness in Caledon ranging from 84.64% to 95.82%, and in Heidelberg ranging from 93.97% to 96.97%. With regards to screenings, some cultivars in Caledon exceeded the maximum acceptance level of 5%. For instance, Hessekwa (2012) exhibited a screenings percentage of 5.38%, Agulhas (2009) showed 5.32%, and Disa (2006) had the highest screenings at 7.4%. Conversely, the lowest screenings were observed in the cultivar released in 2019, with Bitou showing only 1.5%. In Heidelberg, screenings were lower across all cultivars, with the highest observed in Erica (2004) at 1.8% and the lowest in Malgas (2020) at 0.63%.

6.3 Recommendations

- Plant newer cultivars like Kadie, Bitou, and Malgas for high or low rainfall areas to achieve high yields and select shorter varieties like Malgas for lodging resistance.
- Select newer cultivars for breeding to maintain high plumpness levels above 80% while minimizing screenings below the maximum acceptance level of 5% to meet malting quality standards.

- The contrasting correlation between total kernel nitrogen content and cultivars released in different years warrants further investigation. Future research should aim to understand the underlying factors influencing nitrogen content and its implications for malting quality.

6.3 References

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